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MEASUREMENT OF  
OPTICAL RADIATIONS

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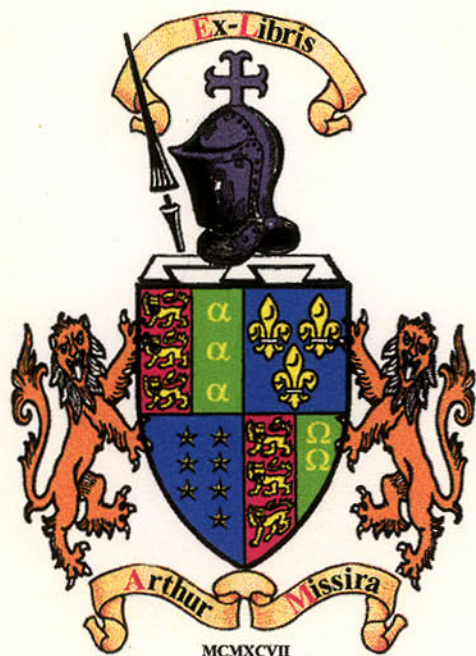
MEASUREMENT OF OPTICAL RADIATIONS




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**MEASUREMENT OF  
OPTICAL RADIATIONS**





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# MEASUREMENT OF OPTICAL RADIATIONS

*The detection of electromagnetic radiation  
from ultra-violet to infra-red*

*Georg Bauer*



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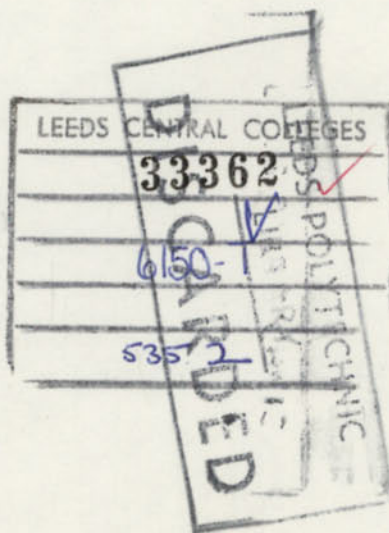
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### ERRATA

- p. 19, first line: for " $f_0/r^2$ " read " $f/r^2$ ".
- p. 21, equation (9a) should read " $E = \Phi/f_2 = I \cos \varepsilon_2/r^2$ ".
- p. 33, after equation (26): for "radiant intensity" read "radiance".
- p. 53, lines 10, 13, 14: for "radiant intensity" read "radiance".
- p. 61, Section 2, first line: for "radiant intensity" read "radiance".
- p. 63, end of the caption for Fig. 42 should read: " $\varphi$  = aperture angle;  $\varphi_1 \approx \varphi_2$ ".
- p. 65, Section 6, lines 16, 17: for "radiant intensity" read "radiance".
- p. 66, Section 2, line 7: for "irradiation intensity" read "irradiance".
- p. 68, Section 4, line 3, Section 5, line 5: for "irradiation intensity", read "irradiance".
- p. 69, line 2: for "radiation intensity" read "irradiance".
- p. 75, line 4: for "irradiation intensity" read "irradiance".
- p. 87, caption for Fig. 58: for "radiation intensity" read "irradiance".
- p. 96, last but one line: for "filament lamp" read "incandescent lamp".
- p. 115, equation (59) should read " $C = l \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r \tau(\lambda) s(\lambda) d\lambda$ ".



## FOREWORD

The measurement of electromagnetic radiation of the optical region of the spectrum has lately considerably increased in importance. The two main reasons for this are:

- (1) Increasing use is made of objective measurement methods for both light and colour measurement;
- (2) The practical importance of the ultra-violet and infra-red bands has increased over a wide field of applications.

It seemed therefore useful to survey the principles of the methods of measurement in this band of wavelengths, limiting the subject matter to the general principles and the measurement of radiators and detectors. In the space available it was not possible to discuss special variations as required for instance in the far infra-red band.

The bibliography lists comprehensive works and monographs which, in turn, refer to other sources. The selection of original works has, of course, not been at random. Its purpose is to offer the reader who wishes to extend his knowledge a reliable initial guide.

This book is intended for anyone having to deal with the measurement of electromagnetic radiation in the optical spectrum. It is meant to perform the dual role of introduction and survey. As far as possible, hints for experiments have been given, but only to a very limited extent.

Finally a word on nomenclature. The subject matter of this book is also often called "spectrophotometry." As our subject ranges over a far wider field than the measurement of radiation dispersed into a spectrum, and as furthermore the term "photometry" nowadays is reserved for illumination technique, the term spectrophotometry has been avoided.

I am most indebted to Prof. Dr. Ebert for his valuable counsel, Dr. K. Bischoff for reading the MS. and unstinting advice and finally K. Stübenrath and W. Meier for assisting in the preparation of the illustrations.

## INTRODUCTION

The word radiation is nowadays used in many senses: X-rays, alpha-rays, acoustic and heat radiation, to mention only a few. All these phenomena have a common denominator; that there is always a propagation of energy, which, in individual cases, may take place in very different ways. X-rays, for instance, are electromagnetic waves of very short wavelength, while in the case of alpha-rays we have to deal with fast moving helium nuclei. Acoustic radiation is the name for the spreading of fluctuations of pressure in the form of sound waves and heat radiation is electromagnetic radiation of long wavelength.

In this book we shall only deal with electromagnetic radiation of the kind which can be dealt with by the usual optical apparatus. Optics itself—often also called the science of light—is only concerned in the first place with the visible spectrum from about 380 to 780  $m\mu$ .\*<sup>2</sup> In the adjacent regions of shorter or longer wavelengths the methods of radiation generation and measurement are within certain limits the same. The region which begins at about 10  $m\mu$  and ends at about 0.1 mm which is also called nowadays the optical region of the spectrum is the subject of this book.

Originally, the term "light" was used to designate the entire optical region of the spectrum, which included the immediately adjacent ultra-violet and infra-red regions. This is understandable from a historic point of view, because the study of electromagnetic radiation originated in the region visible to the human eye. After objective methods of measurement had been evolved, the research was continued in the adjacent bands of the spectrum.

Lately it has become the rule to term "light" the visible spectrum and simply to use the term "radiation" when speaking of the entire optical region of the spectrum.<sup>2,8</sup> This terminology is not entirely satisfactory as we have seen that the term "radiation" is now being applied in so many senses. In the absence of specific information, misunderstanding may occur.

The differentiation between "light" and "radiation" not only concerns the spectrum range but also the problems of measurement. Radiation, as a form of energy, is measured in energy or power units, e.g. in watt-seconds or watts. Visible light is measured in specific units which take into account the sensitivity of the eye for light of different wavelengths.

When, therefore, we use the term "radiation measurement in the optical spectrum" we mean the measurement of electromagnetic radiation energy in the wavelength band between approx. 10  $m\mu$  and 0.1 mm.

---

\* 1  $m\mu$  =  $10^{-9}$  metre, in process of replacement by 1 nm.

# I. GENERATION AND PROPERTIES OF ELECTRO-MAGNETIC RADIATION

## 1. Wave and quantum representation

The generation and absorption of electromagnetic radiation is always bound up with changes in the energy of electrically charged particles; the basic concepts, however, are not uniform.

In the X-ray region and short-wavelength optical region of the spectrum we must start from the "quantum jumps," i.e. the spontaneous changes of electron energy within the atom according to the quantum theory. In the long-wave optical region vibration and rotation processes occur within the molecule, while in the field of electric waves, i.e. high-frequency technique, a description based on the classical concept of vibrating electrical charges is permissible.<sup>1,5,12,15</sup>

For describing many phenomena one uses the concept of a wave advancing by a simple harmonic oscillation of the electromagnetic field transverse to the direction of propagation. The frequency  $\nu$  of the wave motion is the number of oscillations per unit time. The period  $T$  of the motion is the time in which the wave moves a distance of one wavelength. If the velocity is  $c$  and the wavelength  $\lambda$  there are the following relationships between these quantities:

$$\lambda = cT = c/\nu \quad (1)$$

The unit of frequency is 1 cycle per second (cps), sometimes referred to as 1 hertz.

This concept, however, is not always sufficient, and in many cases one must consider radiation energy as consisting of multiples of an indivisible quantity called a quantum with an energy  $A$ :

$$A = h\nu \quad (2)$$

where  $h = 6.625 \cdot 10^{-27}$  erg-sec (Planck's constant<sup>4,15</sup>).

The velocity of electromagnetic radiation, i.e. the velocity of light, is highest in *vacuo*  $c_0 = 2.99792 \cdot 10^{10}$  cm/sec.<sup>4,15</sup>

## 2. Wavelength and spectrum

Different units are in use for designating wavelength:

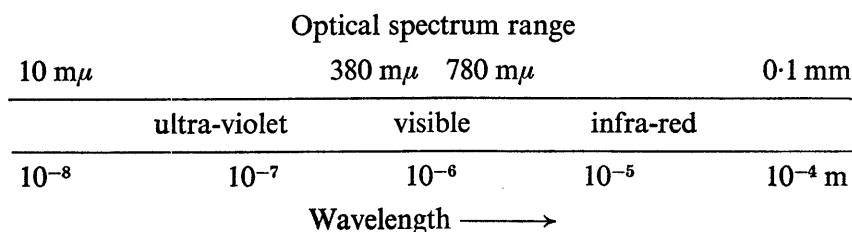
Infra-red	$1 \mu$ or $1 \mu\text{m} = 10^{-6}$ m (micron)
Visible spectrum and ultra-violet	$1 \text{ m}\mu$ or $1 \text{ nm} = 10^{-9}$ m (millimicron)
Spectroscopy	$1 \text{ \AA} = 10^{-10}$ m (Ångstrom)
X-rays	$1 \text{ X} = 10^{-13}$ m



Although frequency is the physically most important value (since wavelength varies if the velocity changes, as it does in going from one medium to another) it is usual to represent electromagnetic radiation by its wavelength. The exceedingly small difference between the wavelength in a vacuum and in air is nearly always negligible.

Another unit, used in spectroscopy for indicating the number of waves in unit length, is the wave number, usually expressed in  $\text{cm}^{-1}$ .

The following diagram represents the range of electromagnetic waves under discussion:<sup>2,8</sup>



A number of sub-divisions have been established in practice, which are only partly binding:

10–200 $\text{m}\mu$	Vacuum ultra-violet. As atmospheric absorption begins to be objectionable at wavelengths below 200 $\text{m}\mu$ it is necessary to work in a vacuum.
200–300 $\text{m}\mu$	Short ultra-violet.
300–380 $\text{m}\mu$	Near ultra-violet.
380–780 $\text{m}\mu$	Visible spectrum.
780 $\text{m}\mu$ –2.5 $\mu$	Near infra-red.
2.5 $\mu$ –15 $\mu$	Medium infra-red.
15 $\mu$ –0.1 mm	Far infra-red.

For biological purposes, a special sub-division of the UV range is usual in Germany<sup>2</sup>:

10–280 $\text{m}\mu$	UV-C
280–315 $\text{m}\mu$	UV-B
315–380 $\text{m}\mu$	UV-A

There is a tendency towards international standardization of these descriptions, but this has not as yet been achieved.

### 3. Other properties

Electromagnetic radiation is also characterized by its state of polarization. As we are dealing with transverse waves, the electrical and magnetic fields of the wave, whose directions are always at right angles to each other and to the direction of propagation, waves can assume special forms of vibration. When these fields have a fixed direction, we call the radiation plane-polarized. Circular or elliptic polarization occurs when the directions of the fields vary with time. But as a general rule, electromagnetic waves vibrate in all possible directions at right angles to the direction of propagation, so that the radiation is non-polarized.

Interference belongs to the same order of ideas. This is the consequence of superposing two waves of the same wavelength and it depends on the phase relation between them whether the resultant amplitude is greater or smaller; polarization also plays a part.

When electromagnetic rays strike a body, part will be reflected by the surface and part will penetrate into the body. Reflection can be regular (specular) or diffuse. For regular reflection of a narrow pencil of rays, the well-known law applies that the angle of reflection is equal to the angle of incidence and that the reflected ray, the incident ray and the normal to the surface at the point of incidence, all lie in the same plane.

Radiation which enters the body is partly absorbed and partly transmitted. A residual amount finally emerges from the body after reflection by the exit surface or after multiple reflections inside the body, and is added to the radiation already reflected by the incident surface. In the case of specular incident radiation, the transmitted radiation can remain specular, which is the case with transparent media, e.g. a piece of coloured glass. But it can also occur that the transmitted rays emerge in all directions (e.g. in a cloudy fluid). Then one speaks of scattered radiation or diffuse transmission.

When a narrow pencil of rays passes from one medium into another, its direction is changed. This is termed refraction. Here, Snell's law applies: incident ray, refracted ray and normal, all lie in one plane, while the ratio of the sine of the angle of incidence ( $\alpha$ ) to the sine of the angle of refraction ( $\beta$ ) is constant:

$$\sin \alpha / \sin \beta = n_{1,2} \quad (3)$$

$n_{1,2}$  is known as the index of refraction for the two media (1 and 2). In conformity with the wave-like nature of radiation, refraction is simply a result of the different velocities in the respective media.

One of the three values, reflection, absorption and transmission, can be of major importance and so make the other two negligible.

Examples: *Main effect reflection: mirror (regular); white surface (diffuse)*

*Main effect absorption: black surface*

*Main effect transmission: window pane (regular); ground-glass (diffuse)*

#### 4. *Excitation and forms of radiation*

When the radiation is emitted by atoms, without much interaction, the radiation will be limited to individual, narrow wavelength bands, so narrow that they can be described by single wavelengths. By studying radiation dispersed through a spectroscope, these single wavelengths will appear as relatively sharp lines. Such a spectrum is called a line spectrum and is generated by line-spectrum radiators. This kind of excitation is found to a high degree in the gas discharge lamp at rather low pressure, in electric sparks and in the arc lamp.

If, however, there is a great amount of atomic interaction in the source of radiation, the radiation corresponding with a line is spread over a larger wavelength band. The spectroscope shows the spectrum as a continuous band, so that we can speak of a continuous-spectrum radiator.

The spectrum of a radiator is the arrangement in band or lines of the radiated waves in order of their frequencies.

All bodies emit continuous radiation since their temperature is always higher than  $0^{\circ}\text{K}$ . In this case the term thermal radiator (or heat radiator for long-wave thermal radiation) is applicable.

Gas discharges at high pressure also give a preponderant continuous spectrum, but with superimposed lines.

The thermal radiation of what is called a "black body" is of the utmost importance. According to the impression made on the human eye, a surface is called "black" when it completely absorbs all radiation, i.e. does not reflect any incident radiation. Although this definition was first used for visible light, it is now also applied to other wavelength bands.

An ideally black body does not exist in nature. Even in limited wavelength bands, the best that can be expected is a very high degree of absorption with little dependence on wavelength. If absorption is independent of wavelength, the surface under observation is termed "grey," without reference to the degree of absorption. This term, too, is valid not only in the visible spectrum, but also throughout the entire optical spectrum.

It is possible to realize a black body (or total radiator) to any degree of approximation. All that is needed is to make a small aperture in a hollow sphere and observe the absorption of this aperture. It is immaterial how great the absorption (or reflection) of the inside wall of the sphere is. The resulting extremely small quantity of reflection can be reduced to any desired degree by increasing the ratio of inside area to aperture diameter.

The reason for this is that by far the largest part of the incident radiation can only emerge from the aperture after a very great number of reflections. As each reflection absorbs a certain part of the radiation, however small, one has only to ensure that the number of reflections is high enough to yield any desired reduction in radiation.



When the inner surface of the sphere has a temperature exceeding  $0^{\circ}\text{K}$ , the cavity simultaneously acts as a radiator in such a way that the aperture radiates like a black body, the temperature of the inner surface being considered uniform. In this manner, an approximation to a total (or black body) radiator can be achieved.

The output of energy from thermal radiation increases considerably with rising temperature. The emission of energy is independent of the fact that there may be other radiators in the proximity. The transfer of energy by radiation between two bodies of different temperatures is determined by the temperature difference between the two individual radiators. Only the absorbed radiation matters. The warmer body always transfers energy to the cooler body; if both bodies are of the same temperature, no energy transfer by thermal radiation takes place. This rather obvious statement leads to the relationship between emitted and absorbed radiation, which will be discussed in Chapter III.

## II. QUANTITATIVE CHARACTERISTICS OF RADIANT ENERGY

### 1. Radiators

The propagation of radiant energy is described by means of a number of descriptive quantities of an essentially geometric character.<sup>2,4,7,8,9</sup> The simplest way to proceed is by means of the following diagram which can be applied in any optical system (see Fig. 1):

The radiator, sometimes called the source, is represented by a small radiant surface  $f_1$ . The radiation is observed from a direction forming an angle  $\epsilon_1$  with the normal to the surface  $f_1$ . The equally small receiving surface  $f_2$  receives the radiation at an angle  $\epsilon_2$  to the normal to the surface  $f_2$ . The distance  $r$  between radiator and receiver should be so great that it has the same value for all points of  $f_1$  and  $f_2$  with sufficient accuracy. If this condition is met, one can proceed to calculate with fixed, single values of  $\epsilon_1$  and  $\epsilon_2$ .

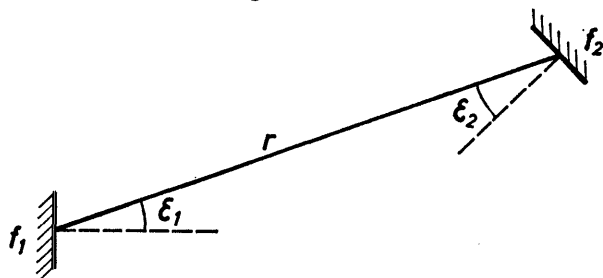


Fig. 1 Propagation of radiation.

Starting with total quantity of radiant energy  $Q$ , the power, more often known as the radiant power or radiant flux  $\Phi$  is found by differentiation with respect to time  $t$ :

$$\Phi = dQ/dt \quad (4)$$

When  $Q$  is expressed in joules and  $t$  in seconds,  $\Phi$  will be expressed in watts (1 watt = 1 joule/sec).

Flux is emitted by  $f_1$  in all directions and only that part strikes the receiver surface  $f_2$ , which is included within the solid angle  $\omega$  given by

$$\omega = (f_2^*/r^2) = (f_2 \cos \epsilon_2/r^2) \quad (5)$$

where  $f_2^*$  is the projection of  $f_2$  on a plane normal to the direction of observation. The unit of solid angle is the steradian (sr).

Note: The magnitude of the solid angle is defined as the area  $f_0$  of the surface, which is described by the intersection of a cone of rays with the surface of a unit sphere, i.e. a sphere with a radius = 1. If the sphere is changed to one of radius  $r$  and the corresponding intersected area is  $f$ , the area on the unit sphere

is  $f_0/r^2$ . If  $r$  has a sufficiently great value relative to the area, a flat surface will be a sufficient approximation to the corresponding spherical cap (see Fig. 2).

In the form of an equation:

$$\{\omega\} = \{f_0\} = f/r^2$$

As the ratio between an area and the square of a distance, the solid angle itself is of zero dimensions. Of late, however, the steradian (sr) has been used, as a description of the unit, i.e. of the solid angle subtended at the centre of a sphere by an area on its surface numerically equal to the square of the radius. Therefore:

$$\omega = f/r^2 \text{ sr}$$

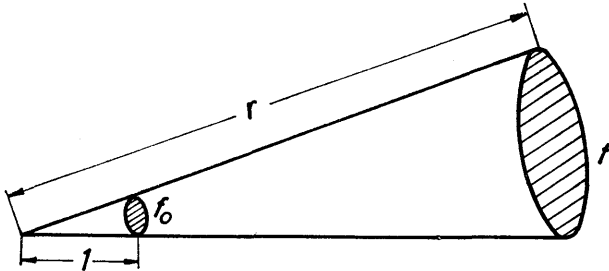


Fig. 2 Definition of solid angle.

Now the radiant flux is not necessarily uniform throughout all directions in space. In order to represent what happens we need to know the ratio of the flux  $d\Phi$  within a given infinitesimal solid angle  $d\omega$  for all directions. The quantity  $d\Phi/d\omega$  is called the radiant intensity

$$I = d\Phi/d\omega = d^2Q/dt d\omega \quad (6)$$

This definition implies that the radiation comes from a point source or an infinitesimal element of area of a finite source. Other cases require the assumption that the source is at a distance large compared with the dimensions of the source.

In many cases, when the source is of appreciable size, it is its apparent size which matters. The radiant intensity per unit area (or radiance)  $L$  is then the quotient of the radiant intensity in the given direction of an infinitesimal element of area by the apparent size seen from the given direction;

$$L = dI/df_1 \cos \varepsilon_1 = d^2\Phi/d\omega df_1 \cos \varepsilon_1 = d^3Q/dt d\omega df_1 \cos \varepsilon_1 \quad (7)$$

When  $f_1$  is expressed in square centimetres,  $L$  will be expressed in watt/cm<sup>2</sup>. steradian.

For the special case when  $I$  is proportional to the cosine of the angle  $\varepsilon_1$  to the normal to the surface and does not depend on the azimuth,  $L$  becomes independent of the direction of radiation. We now find:

$$I = I_0 \cos \varepsilon_1; \quad L = I/f_1 \cos \varepsilon_1 = I_0/f_1 \quad (7a)$$

where  $I_0$  = radiant intensity in the direction of the normal to the surface.

This is Lambert's law. A radiating surface then appears to have the same brightness when observed from any angle, because the radiant intensity per unit apparent area remains constant.



When Lambert's law holds and the values of  $I$  are plotted as vectors on a plane at right angles to the radiant surface, the polar diagram of the radiance is a circle of diameter  $I_0$  (see Fig. 3).

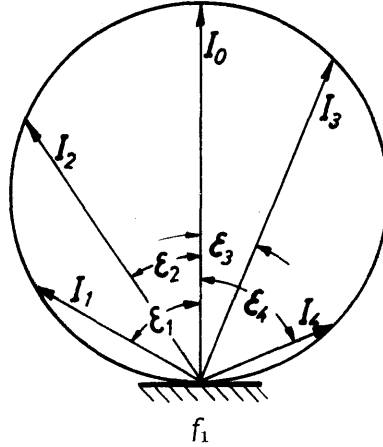


Fig. 3 Polar diagram of radiant intensity when Lambert's law is obeyed.

One is also often interested in the total radiant flux per unit area which is propagated through the entire hemisphere (i.e. of solid angle  $2\pi$  sr; symbol  $\ominus$ ). This radiant emittance  $M$  is defined by the equation

$$M = \int_{\ominus} (d^2\Phi/df_1 d\omega) d\omega \quad (8)$$

$M$  is obtained in watts/cm<sup>2</sup> by using the usual units.

$M$  takes a much simplified form when Lambert's law applies as follows by referring to equations (6) and (7a):

$$M = \int_{\ominus} (dI/df_1) d\omega = \int_{\ominus} L \cos \epsilon_1 d\omega = \int_0^{\pi/2} L \cos \epsilon_1 2\pi \sin \epsilon_1 d\epsilon_1 = \pi L \quad (8a)$$

## 2. Detectors

So far, the characteristic quantities and units relate to the energy emitted by a radiator. We shall now discuss the conditions at the receiver situated in the radiation field of the radiator.

The fundamental value here is the irradiance, namely the quotient of the radiant power incident on an element of infinitesimal area of surface (of a receiver) by the area of the element obtained by differentiating with respect to the receiver surface. The value thus obtained is

$$E = d\Phi/df_2 \quad (9)$$

When using the accepted physical units,  $E$  will be expressed in watts/cm<sup>2</sup>.

The above definition is valid whatever the angle of the incident radiation. Assuming that the radiation comes from a small source and is received on a small receiver at a considerable distance simplified formulae can be used and the following equations are valid for radiator and receiver. Equations (5) and (6) give:

$$\Phi = I\omega = I(f_2 \cos \varepsilon_2 / r^2) \quad (6a)$$

therefore:

$$E = \Phi / f_2 = I \cos \varepsilon_2 / r^2 \quad (9a)$$

In the case of the receiver area being at right angles with the radiator area, we find:

$$E_{\perp} = I / r^2 \quad (9b)$$

This is the inverse square law.

By replacing  $I$  in equation (6a) according to equation (7) by  $L \cdot f_1 \cos \varepsilon_1$ , we have:

$$\Phi = L(f_1 \cos \varepsilon_1 f_2 \cos \varepsilon_2 / r^2) \quad (6b)$$

This is the basic equation of photometry. It states that the incident radiation on a receiver surface  $f_2$  varies directly with the surface areas  $f_1$  and  $f_2$  and with the cosines of the angles of inclination  $\varepsilon_1, \varepsilon_2$ ; and varies inversely as the square of the distance  $r$ . The proportionality factor is the radiant intensity per unit area  $L$ , which, generally speaking, varies with direction. Only when Lambert's law applies is  $L$  the same for all directions.

Equation (6b) shows a noteworthy symmetry. It shows immediately that  $f_1$  will receive the same radiant flux when this surface is used as receiver and  $f_2$  as radiator, at a constant value of  $L$ .

In certain practical applications, the radiant energy per unit of receiver area is of significance; this is called the irradiation. If it is called  $H$  then

$$H = dQ/f = \int_0^t E dt \quad (10)$$

and is equivalent to the exposure in photography.

When using the standard primary units,  $H$  is expressed in joules/cm<sup>2</sup>.

### 3. *Spectral concentrations and radiation distribution*

So far, no account has been taken of the fact that all these values generally depend on the wavelength. In the case of radiant energy production it is, however, impossible to ascribe a finite energy amount to an individual wavelength. Even the most sharply defined spectral line has a finite width, i.e. we must ascribe to the line a finite wavelength interval.

The emitted radiant energy must therefore be reckoned as energy per unit band of wavelength, or more exactly as the quotient of energy within an infinitesimal range of wavelengths divided by the range, to make the concept of

spectral distribution intelligible. In this way, spectral (monochromatic) values are obtained for all the characteristic quantities. They are indicated to be so by the subscript  $\lambda$ . Thus:

$$Q_\lambda = dQ/d\lambda, \quad I_\lambda = dI/d\lambda, \quad L_\lambda = dL/d\lambda, \text{ and so on} \quad (11)$$

In practice, the spectral range  $\Delta\lambda$  is often small. The radiation value concerned is found by multiplying the spectral value by  $\Delta\lambda$ . For example, we obtain for a radiant flux  $\Delta\Phi$  in the wavelength range  $\Delta\lambda$  a value of

$$\Delta\Phi = \Phi_\lambda \Delta\lambda \quad (11a)$$

Obviously, the spectral values are also dependent upon the wavelength and the subscript  $\lambda$  is usually taken as a sufficient indication that this is so. But when the value of a spectral quantity  $E_\lambda$  is meant for a given wavelength, e.g.  $\lambda_0$ , the full expression  $E_\lambda(\lambda_0)$  will be used.

*Note, however, that the dimensions of these spectral quantities will depend, in particular, on the unit of wavelength.*

Examples:

$$\begin{aligned} \Phi &\text{ in } w; \quad \Phi_\lambda \text{ in } \frac{w}{\text{cm}} \text{ or } \frac{w}{\text{m}\mu} \\ L &\text{ in } \frac{w}{\text{cm}^2\text{sr}}; \quad L_\lambda \text{ in } \frac{w}{\text{cm}^3\text{sr}} \text{ or } \frac{w}{\text{cm}^2\text{m}\mu \text{ sr}} \\ E &\text{ in } \frac{w}{\text{cm}^2}; \quad E_\lambda \text{ in } \frac{w}{\text{cm}^3} \text{ or } \frac{w}{\text{cm}^2\text{m}\mu} \end{aligned}$$

Quantities such as those given in the above examples are referred to as spectral concentrations. In place of wavelengths, frequencies, wave-numbers or their logarithms may be used: if there is any risk of ambiguity it is necessary to speak of "spectral concentration in terms of frequency" (or other variable).

The relationship between the radiant energy and the wavelength of the radiation from a source is called "spectral radiation or energy distribution." When this relationship is only relative (usually with the maximum value as unity) we speak of "relative spectral distribution."

For example, with reference to a radiant flux  $\Phi_\lambda$ , the relative spectral distribution  $(\Phi_\lambda)_r$  can be expressed as the ratio between the radiant flux  $\Phi_\lambda$  and the value of the flux at a given wavelength  $\lambda_0$

$$(\Phi_\lambda)_r = \Phi_\lambda / \Phi_\lambda(\lambda_0) \quad (12)$$

The same values would be obtained when different radiation quantities have to be considered, since the latter (according to equations (4) to (11)) will show the same spectral dependency as the radiant flux. Hence the very general expression "spectral distribution."



Equation (12) gives:

$$\Phi_{\lambda} = \Phi_{\lambda}(\lambda_0) \cdot (\Phi_{\lambda})_r = \text{const.} \cdot (\Phi_{\lambda})_r \quad (12a)$$

When, therefore, the relative spectral radiation distribution is known, it is only necessary to determine the constant  $c = \Phi_{\lambda}(\lambda_0)$ , to obtain the absolute value at any wavelength. It is sufficient to carry out an absolute measurement at any desired wavelength  $\lambda_n$ ; because equations (12) and (12a) give:

$$\text{const.} = \Phi_{\lambda}(\lambda_0) = \Phi_{\lambda}(\lambda_n) / \Phi_{\lambda}(\lambda_n)_r \quad (13)$$

The values of the constant thus obtained are always specific to the quantity concerned; in this case to the spectral radiant flux and the constant  $c = \Phi_{\lambda}(\lambda_0)$  must be expressed in the units appropriate to the quantity to which it relates, e.g. in equation (13),  $\text{W/m}\mu$ .

When a spectral quantity is constant (independent of wavelength) we speak in our present units of an equal energy spectrum. The corresponding relative spectral radiation distribution is then also constant and equals 1.

In many cases we wish to know the total emission for a more extended wavelength band. This is calculated by integration with respect to the spectral quantity concerned, e.g. for the radiation flux:

$$\Phi = \int_{\lambda_1}^{\lambda_2} \Phi_{\lambda} d\lambda \quad (14)$$

If the integration applies over all wavelengths, the "total radiation" is obtained; in our example therefore the total radiant flux.

In the case of a line spectrum, the integration interval  $\lambda_1$  to  $\lambda_2$  (the "natural line width") is so small that the total radiation can be attributed to a line of an average wavelength. This wavelength is added in brackets, so that  $\Phi(\lambda)$  is used for the radiant flux of a line of the corresponding average wavelength  $\lambda$ .

#### 4. *Graphic representation of radiation distribution*

For the graphic representation of a continuous spectrum, the spectral distribution curve can be recorded, e.g. the spectral concentration can be plotted against the wavelength. The total emission then corresponds with the area enclosed by the curve (see Fig. 4).

This way of representation is not satisfactory in the case of a line spectrum, because the widths of the individual lines are small compared with the intervening gaps and it is impossible to make a graph of a large spectral region. Moreover, the spectral radiation distribution within the lines is in most cases of little importance and often, only the total emission of each of the lines is known.

In this case, the total emission of a line is ascribed to a single average wavelength and represented by a line of a length which is the measure of the

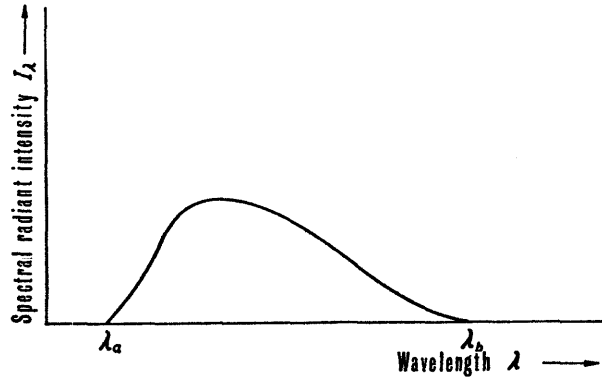


Fig. 4 Spectral distribution of a continuous radiator.\*

$$\text{Radiant Intensity } I = \int_{\lambda_a}^{\lambda_b} I_{\lambda} d\lambda.$$

total emission. The total emission of a radiator emitting more than one line is then the sum of these lines (see Fig. 5).

When it is required to represent a mixed spectrum (continuous + lines) there are difficulties. If the spectral concentration is chosen, the small intervals of wavelength already mentioned as necessary for representing lines will cause

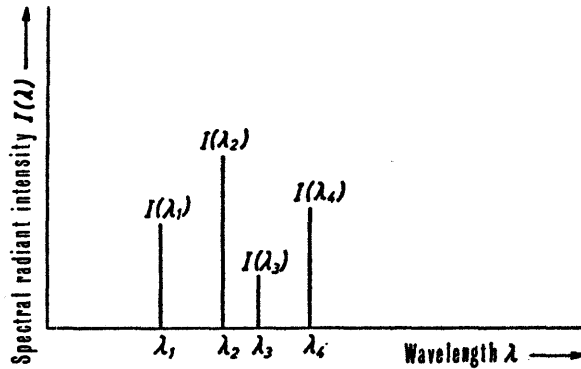


Fig. 5 Spectral distribution of a line radiator.

$$\text{Radiant Intensity } I = I(\lambda_1) + I(\lambda_2) + I(\lambda_3) + I(\lambda_4) = \sum_{v=1}^{v=4} I(\lambda_v).$$

difficulties. Furthermore, the spectral concentrations are usually of a different order of magnitude for the continuous spectrum and for the line spectrum. For this reason, graphical representation by means of spectral concentrations is hardly ever possible. There are, however, two alternative methods:

\* In this and similar figures the ordinates have been described as "Spectral radiant intensity" in place of the technically more accurate expression "Spectral concentration of radiant intensity" in order to save space.

(1) The spectral concentration is chosen as a starting point and the lines are given an arbitrary, large wavelength width and a correspondingly smaller spectral concentration. Each line is thus represented as a rectangle, the area of which corresponds with the total emission of the line. No physical significance applies separately to the wavelength widths, which may conveniently be made of the same size for all lines, or the value of the spectral concentration (see Fig. 6).

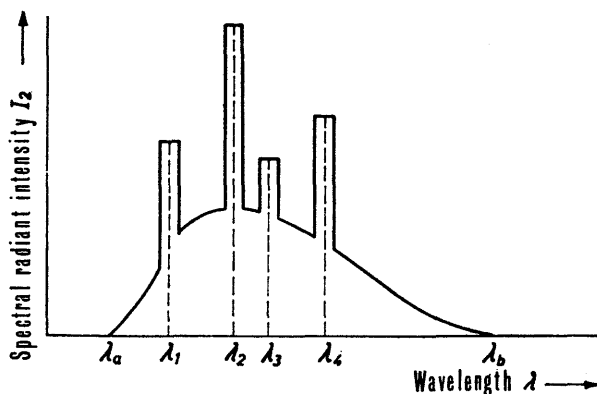


Fig. 6 Spectral emission of a mixed radiator I.

$$\text{Radiant Intensity} = \int_{\lambda_a}^{\lambda_b} I_{\lambda} d\lambda.$$

(2) The continuous spectrum is divided into equal wavelength intervals and the ordinate at the mean wavelength of each interval given such a length as to represent the total emission within the interval (see Fig. 7).

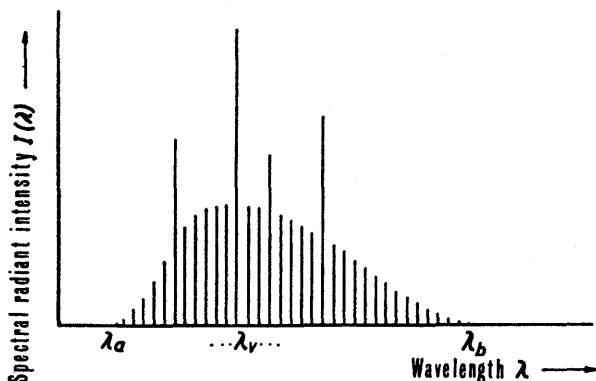


Fig. 7 Spectral emission of a mixed radiator II.

$$\text{Radiant Intensity } I = I(\lambda_1) + I(\lambda_2) + \dots + I(\lambda_n) = \sum_{v=1}^{v=n} I(\lambda_v).$$



In the first case the lines can be considered as being transformed into continuous spectra, whilst in the second case, the continuous spectrum is split up into separate equidistant lines.

We should note that it is also possible to represent the total emission as a function of the wavelength bounding the region of the spectrum within which the total emission is calculated. This applies also to the radiant intensity:

$$I = \int_{\lambda_a}^{\lambda} I_{\lambda} d\lambda \quad (14a)$$

This curve is derived from the curve of spectral concentration by integration, while conversely the spectral concentration can be obtained from the integral curve by differentiation (Fig. 8).

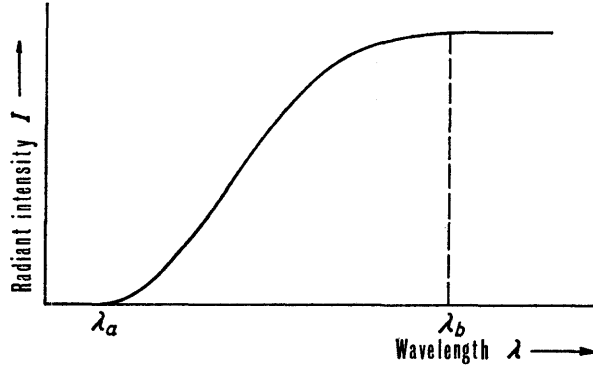


Fig. 8 Emission of a continuous radiator.  
Spectral concentration of radiant intensity  $I_{\lambda} = dI/d\lambda$ .

We should mention that the form of the curve in such a graphical representation, particularly with respect to the position of maximum values, depends on the abscissa variable. For instance, instead of the wavelength, the frequency  $\nu$  could be chosen as variable and a completely new curve would result.<sup>164</sup>

##### 5. Reflection, absorption, transmission

Only relative values of radiant fluxes (i.e. pure numerical values) can be obtained for reflection, absorption and transmission. It is usual to call the corresponding quotients: reflection factor (U.K.), reflectance (U.S.A.)  $\rho$ ; absorption factor (U.K.), absorptance (U.S.A.)  $\alpha$ ; and transmission factor (U.K.), transmittance (U.S.A.)  $\tau$ .<sup>9,30</sup> These values indicate the fraction of the incident radiation, which is reflected, absorbed or transmitted. If  $\Phi$  be the incident radiant flux,  $\Phi_{\rho}$  the reflected,  $\Phi_{\alpha}$  the absorbed and  $\Phi_{\tau}$  the transmitted radiant flux, then:

$$\rho = \Phi_{\rho}/\Phi, \quad \alpha = \Phi_{\alpha}/\Phi, \quad \tau = \Phi_{\tau}/\Phi \quad (15)$$

$$\Phi_{\rho} + \Phi_{\alpha} + \Phi_{\tau} = \Phi; \quad \rho + \alpha + \tau = 1 \quad (16)$$

The quantities so defined are "mixed" in the sense that the reflected light consists not only of light reflected from the front surface of the object, but also some which has entered the object (and some of which is therefore absorbed) and then been reflected out; the transmitted light is not only that which has passed directly through the object but has added to it a component which has been reflected back at the exit surface and again internally from the entrance surface. In such circumstances the absorption is always derived from measurements of  $\rho$  and  $\tau$ , by the relation (16). Measurements of "pure" reflection factor and "pure" absorption factor need special techniques, either of measurement or calculation.

We should, however, bear in mind that absolute values of these factors can only be defined for monochromatic radiation. This means limitation of the radiation to a very small wavelength range  $\Delta\lambda$ , to which we attribute a mean wavelength  $\lambda_m$ . The corresponding radiation flux  $\Delta\Phi$  is then:

$$\Delta\Phi = \Phi_\lambda(\lambda_m)\Delta\lambda \quad (19)$$

This brings us back to the spectral concentration of radiant intensities introduced in equation (11), which are indicated by the subscript  $\lambda$ . We now obtain the following equation for monochromatic reflection, absorption and transmission:

$$\begin{aligned} \rho(\lambda) &= (\Phi_\lambda\Delta\lambda)_\rho/\Phi_\lambda\Delta\lambda \\ &= (\Phi_\lambda)_\rho/\Phi_\lambda; \quad \alpha(\lambda) = (\Phi_\lambda)_a/\Phi_\lambda; \quad \tau(\lambda) = (\Phi_\lambda)_t/\Phi_\lambda \end{aligned} \quad (20)$$

These also are purely relative values and dimensionless.

Integrating numerator and denominator with respect to a larger spectral region, we arrive at the following values for the total reflection, absorption and transmission factors:

$$\begin{aligned} \rho &= \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \rho(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} \Phi_\lambda d\lambda = \Phi_\rho / \Phi; \\ \alpha &= \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \alpha(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} \Phi_\lambda d\lambda = \Phi_a / \Phi; \\ \tau &= \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \tau(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} \Phi_\lambda d\lambda = \Phi_t / \Phi. \end{aligned} \quad (15a)$$

Note particularly, that the integrated values of  $\rho$ ,  $\alpha$  and  $\tau$  are dependent upon the spectral distribution, here represented by  $\Phi_\lambda$ . According to equation (12a),  $\Phi_\lambda = (\Phi_\lambda)_r \cdot \Phi_\lambda(\lambda_0)$ , where  $\Phi_\lambda(\lambda_0)$  is a constant. When integrating, this constant can be brought outside with integrals and on division disappears. The relative spectral distribution is therefore adequate for these calculations.

## 6. Units used in illumination engineering

Having discussed the most important definitions and units of optical radiation physics, we shall now briefly consider the units used in illumination

engineering. A set of units which corresponds to those used in radiation physics is employed and these can be derived from the latter. In order to take into account the colour sensitivity of the human eye, it is necessary to multiply the physical spectral concentration by the luminous efficiency of each monochromatic radiation  $V(\lambda)$  and to integrate these products over the spectral range of eye sensitivity. In this way the value of the illumination is obtained, a factor determined by the choice of units being included. The spectral sensitivity  $V(\lambda)$  itself is a relative measure to the maximum of sensitivity at  $\lambda = 555 \text{ m}\mu$  being taken as unity. The curve for  $V(\lambda)$  given in Fig. 9 is valid for seeing by any reasonable level of illumination, artificial or daylight. Under bad lighting the eye becomes relatively more sensitive to blue light.

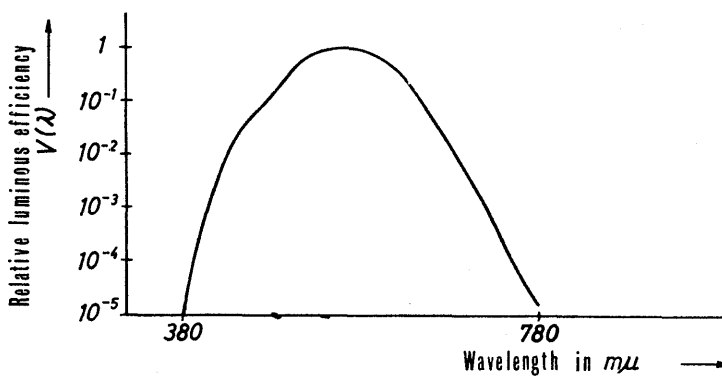


Fig. 9 Spectral sensitivity of the human eye (daylight).

When physical and illumination measurements appear together, difficulties could result, because the same letters are used in both cases as symbols of corresponding units. According to the International Lighting Vocabulary, vol. 1 (2nd edition) of the International Commission on Illumination and the German Standard DIN 5031, the letters when used to denote physical measurements should have the subscript  $e$  added.

But in this book, because no difficulty is likely to arise, the subscript will not be used.

The units used in illumination engineering are based on the unit of luminous intensity which corresponds to radiant intensity. The unit of luminous intensity is the candela (cd) and is so defined that the luminance (i.e. luminous intensity per unit area), corresponding to radiant intensity per unit area of a black body heated to the temperature at which platinum solidifies is  $60 \text{ cd/cm}^2$ . Although many and various units have been devised for illumination engineering, the tendency is towards international standardization and to relate the units directly to the candela. However, the old units persist and the terms "lumen" (lm) for the luminous flux emitted by 1 candela within 1 steradian and "lux" (lx) for the



TABLE 1  
TYPES OF ENERGY, TERMS AND UNITS IN RADIATION PHYSICS AND IN ILLUMINATION ENGINEERING

Type of energy	Symbol	Derivative		Physical		Illumination	
		Correct	Simplified	Term	Unit	Term	Unit
I. Radiators							
Total energy	$Q$	—	—	Radiant energy	w. sec	Luminous energy	lm. sec
Energy per unit time	$\Phi$	$\Phi = \frac{dQ}{dt}$	$\Phi = \frac{Q}{t}$	Radiant flux	w	Luminous flux	lm
Energy per unit time and solid angle	$I$	$I = \frac{d\Phi}{d\omega}$	$I = \frac{\Phi}{\omega}$	Radiant intensity	w/sr	Luminous intensity	cd
Energy per unit time, solid angle and area in direction of emission	$L$	$L = \frac{dI}{df \cos \varepsilon}$	$L = \frac{I}{f \cos \varepsilon}$	Radiance (Radiant intensity/ unit area)	w/sr. m <sup>2</sup>	Luminance	cd/m <sup>2</sup>
Energy per unit time and area	$M$	$M = \frac{d\Phi}{df}$	$M = \frac{\Phi}{f}$	Radiant emission	w/m <sup>2</sup>	Luminous emission	lm/m <sup>2</sup>
II. Detectors							
Energy per unit area	$H$	$H = \frac{dQ}{df}$	$H = \frac{Q}{f}$	Irradiation	w. sec/m <sup>2</sup>	Quantity of illumination	lx. sec
Energy per unit area and time	$E$	$E = \frac{dH}{dt}$	$E = \frac{H}{t}$	Irradiance	w/m <sup>2</sup>	Illumination	lx

When illumination and physical units occur together, the symbols for physical units should be followed by the subscript *e*.

illumination when 1 lumen illuminates 1 square metre uniformly, are still in common use.

The relation between a physical value  $X_e$  and the corresponding illumination value  $X$  is determined by the equation:

$$X = K_m \int X_{e\lambda} V(\lambda) d\lambda \quad (21)$$

The product  $K_m V(\lambda)$  is the ratio of the illumination value to the physical value of a monochromatic radiation of wavelength  $\lambda$ . It is known as the "luminous efficiency". At the maximum of  $V(\lambda)$ , which is at  $555 \text{ m}\mu$ , and has the standardised value of unity, this ratio is equal to

$$K_m = 680 \text{ cd sr/w} \quad (22)$$

The reciprocal of  $K_m$  is sometimes called the "mechanical equivalent of light".

This value is determined essentially by Planck's radiation law and the definition of the candela.

Table 1 lists the names and units used in both radiation physics and illumination engineering.

### III. BLACK BODY AND RADIATION LAWS

#### 1. Planck's radiation law

The exact quantitative relationship between the excitation conditions in a radiator and the type of emitted radiation can only be ascertained for the black body or total radiator. For this reason alone, the black body is of great importance.<sup>2,4</sup> Max Planck's famous radiation law<sup>135,136</sup> gives the spectral concentration of radiance, written with subscript  $s$  to indicate black body radiation (for non-polarized radiation):

$$L_{\lambda,s} = (2c_1/\lambda^5)/(e^{c_2/\lambda T} - 1) \quad (24)$$

The spectral concentration of radiance of the black body therefore depends only on the wavelength  $\lambda$  and the absolute temperature  $T$  (see Fig. 10). The above-mentioned constants  $c_1$  and  $c_2$  can be converted from other more fundamental constants:

$$c_1 = c_0^2 h = 5.953 \cdot 10^{-13} \text{ w.cm}^2 \quad (h = \text{Planck's constant})$$

$$c_2 = c_0 h/k = 1.438 \text{ cm}^\circ\text{K} \quad (k = \text{Boltzmann's entropy constant})$$

$c_0$  is the velocity of light *in vacuo*.

As Lambert's law is rigidly valid for the ideal black body, the following equation for the spectral concentration of radiant emittance can be derived with the help of equation (8a):

$$M_{\lambda,s} = \pi L_{\lambda,s} = (2\pi c_1/\lambda^5)/(e^{c_2/\lambda T} - 1) \quad (24a)$$

#### 2. Wien's law and Rayleigh's law

Apart from the exact Planck's equation, there are two simpler approximate equations appropriate for either small or large values of  $\lambda T$ , which were already known before Planck. These two equations can also be derived from Planck's equation. For small values of  $\lambda T$ , Wien's law<sup>183</sup> is obtained:

$$L_{\lambda,s} = (2c_1/\lambda^5)e^{-c_2/\lambda T} \quad (24b)$$

and for large values of  $\lambda T$ , the Rayleigh-Jeans formula<sup>141</sup>

$$L_{\lambda,s} = 2c_1 T/c_2 \lambda^4 \quad (24c)$$

### 3. Stefan-Boltzmann law and Wien's displacement law

The total radiation is obtained by integrating Planck's equation for all wavelengths between 0 and  $\infty$ , thus arriving at the Stefan-Boltzmann law for the radiant emittance:

$$M_s = \int_0^{\infty} M_{\lambda,s} d\lambda = \sigma T^4 \quad (24d)$$

where  $\sigma = (2\pi^5/15)c_1/c_2^4$  is the Stefan-Boltzmann constant.

The total radiation of a black body therefore increases with the 4th power of the absolute temperature. This relationship was stated by Stefan and Boltzmann (prior to Planck) as the result of thermodynamic arguments.

As the radiator receives an amount of heat corresponding to the ambient temperature  $T_0$ , the following equation accounts for the radiation transferred:

$$M_s^* = \sigma(T^4 - T_0^4)$$

Differentiation of Planck's formula yields Wien's displacement law, which states that the maximum in the spectral concentration of radiant intensity of a black body,  $\lambda_m$ , is displaced towards shorter wavelengths with increasing temperature:

$$\lambda_m T = 0.288 \text{ cm } ^\circ\text{K} \quad (25)$$

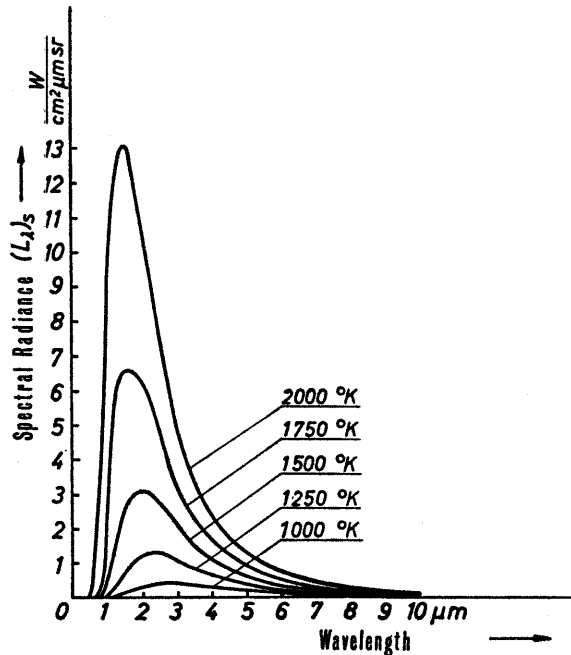


Fig. 10 Black body: isotherms.



Considering the radiation of a thermal radiator and specifically of a black body, at a fixed temperature for different wavelengths, an isotherm is obtained (see Fig. 10). Working with a fixed wavelength and different temperatures, an isochromatic results.

For practical use, tables exist for applying the radiation equations and derived formulae.<sup>37,39,95,107,153,164</sup>

#### 4. Emissivity and Kirchhoff's law

For thermodynamic reasons, no thermal radiator is capable, at any given temperature, of emitting greater radiation than a black body at the same temperature. A measure of the quality of a thermal radiator is therefore its emissivity, that is to say what fraction of black body radiation it emits. The emissivity in general varies with wavelength; it is therefore defined for every wavelength. It also depends on the temperature. In order to take account of possible dependence upon direction, the radiances are taken and we obtain for the degree of spectral emission  $\varepsilon(\lambda)$  in the direction concerned the value:

$$\varepsilon(\lambda) = L_\lambda/L_{\lambda,s} \leq 1 \quad (26)$$

where  $L_\lambda$  is the spectral concentration of radiant intensity of the thermal radiator,  $L_{\lambda,s}$  that of the black body at the same temperature. Fig. 11 shows the degree of spectral emissivity of the technically very important metal tungsten.<sup>178</sup>

A general relationship exists between emissivity and absorption factor. It should first be noted that we consider layers of such a thickness that we can assume the transmission factor to be zero. According to equation (16)  $\alpha = 1 - \rho$  in this case. The absorption factor can therefore be determined by the reflection coefficient, which is the easiest parameter to obtain experimentally.

When the degree of reflection is measured in such a way that the incident radiation has the same direction as that used when determining the emissivity, when the corresponding degree of absorption is calculated, we obtain according to Kirchhoff:

$$\varepsilon(\lambda) = \alpha(\lambda) \quad (27)$$

The spectral emissivity for a given direction therefore equals the spectral absorption factor, measured at the same temperature and for the same direction. Kirchhoff's law is obtained by application of the first and second laws of thermodynamics to observation of the radiation balance in a cavity enclosed by opaque walls of uniform temperature. It states that, in a given direction, a good emitter of a certain wavelength is also a good absorber of that wavelength.

The surface under observation can be of material of any kind, the plane of a section in a radiation-filled cavity, or the radiating aperture of a black body.

When  $\epsilon(\lambda) = \alpha(\lambda)$  and has the same value for all directions, Lambert's law applies for emission, absorption and reflection. Only when this condition is met, can the measurement of reflection be carried out with random direction distribution of the incident radiation and only then is Kirchhoff's law valid without further indication of direction. This is particularly important for the

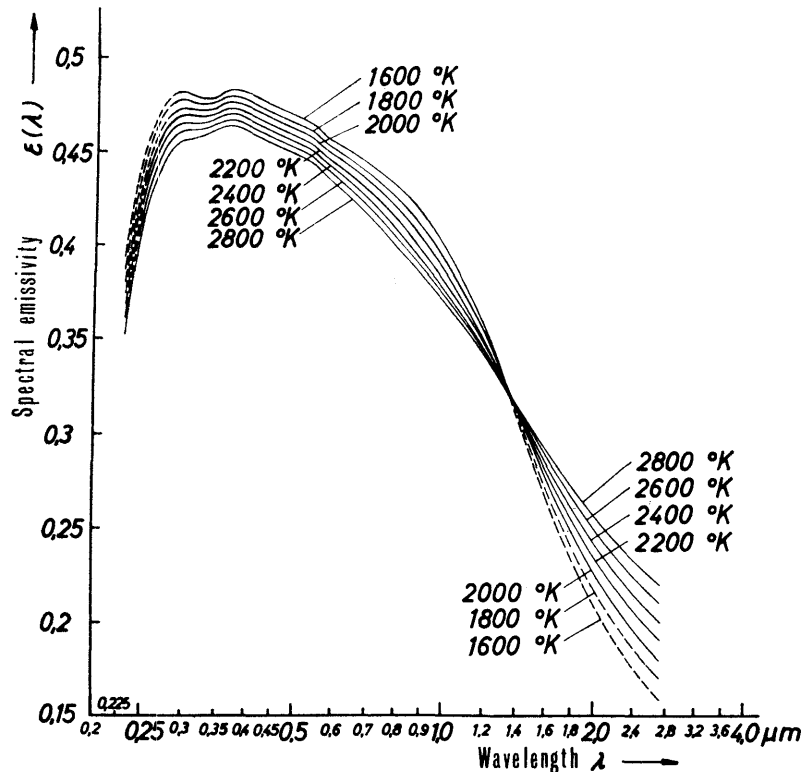


Fig. 11 Emissivity of tungsten (after De Vos). The dotted parts of some of the curves are extrapolated.

realization of a black body radiator, since this is possible to a good approximation only in a given direction.

The emissivity can be defined as a function of the radiant emittance in exactly the same manner. A mean value over all directions is then obtained, which corresponds with the value obtained by assuming that Lambert's law is applicable.

It should be noted that the term "emissivity" is used here in accordance with the latest optical recommendations. In older literature, a variety of terms will be found, or the same term with different meaning. Only the context can show what is meant.

For determining the emissivity, one can consider a larger wavelength band, or the entire wavelength region where the emission is appreciable. In the latter, the total emissivity  $\varepsilon$  is obtained, which depends only upon the temperature:

$$\varepsilon = \int_{\lambda_1}^{\lambda_2} L_{\lambda} d\lambda / \int_{\lambda_1}^{\lambda_2} L_{\lambda, s} d\lambda \leq 1 \quad (26a)$$

As mentioned above, a body is called “grey” in the visible spectrum when it reflects, absorbs or transmits radiation of all wavelengths in the same manner, i.e. unselectively. As emission is related to absorption according to Kirchhoff’s law, a radiator is also called grey when its degree of emission is not dependent on the wavelength:

$$\varepsilon(\lambda_1) = \varepsilon(\lambda_2) = \dots = \varepsilon(\lambda_n) = \varepsilon \quad (26b)$$

### 5. Colour temperature, distribution temperature, black temperature

As it is possible to make such definite statements on the radiation of a black body, it is logical to compare the radiation of any other radiator with a black body. It does not matter if this other radiator is a thermal radiator, another continuous radiator or even a line radiator. The determining value for spectral radiation distribution of a black body is its temperature. It is thus possible to describe the radiation of a radiator by giving the temperature for a corresponding black body. In this way the following definitions can be reached:

#### (a) Colour temperature $T_c$

The colour of a black body is determined by the relative spectral radiation distribution in the visible spectrum. If another radiator gives the same impression of colour, this can be defined by the temperature of a black body having the same colour. This is called the “colour temperature.” As the same colour impression can be created by diverse spectral distributions, even by a suitable set of spectrum lines, the colour temperature does not give a clear indication of the spectral concentration of radiant intensity of the radiator.

#### (b) Distribution temperature $T_d$

The absolute values may be different but it is possible for a certain radiator to have the same relative spectral radiation distribution in a given wavelength band as a black body radiator. This distribution is then characterized by the corresponding temperature of the black body, which is then called the “distribution temperature” in the spectral band concerned. Obviously, it is only possible to speak of distribution temperature with regard to a continuous radiator, but it does not have to be a thermal radiator.

If the distribution temperature applies to the visible spectrum, this is also the colour temperature. For this reason, very often no distinction is made

between distribution temperature and colour temperature in the visible spectrum. This is, however, not completely correct.

It is only rarely possible to determine a distribution temperature.

(c) Black temperature  $T_s$

If measurements are limited to monochromatic radiation, it is possible to compare absolute values, for it is always possible to determine a black body temperature at which the black body has the same spectral concentration as any given radiator. This temperature can be called the "black temperature" for the wavelength concerned. In the case of a thermal radiator, the black temperature is always lower than the true temperature, because the black body radiation attains the same spectral concentration at a lower temperature.

The concept of the black temperature is of particular interest in pyrometry, where the temperature of a distant heat source is ascertained by means of radiation. It is usual to take as reference wavelength  $\lambda = 655 \text{ m}\mu$ , and in the absence of information to the contrary, the black temperature is given for this wavelength.

The "grey thermal radiator" is a special case. For here, according to equation (26b) the spectral emissivity no longer depends on the wavelength, but only on the temperature. In the case of the grey thermal radiator, colour temperature, distribution temperature and true temperature  $T_w$  are all the same, because equation (26) gives the following value for the same true temperature:

$$L_\lambda = L_{\lambda,s} \cdot \varepsilon \quad (26c)$$

This means, however, that the relative spectral radiation distributions are identical, because the constant " $\varepsilon$ " disappears when the relative values are determined. For this reason, the corresponding distribution temperature is the same as the true temperature.

$$\text{Grey radiator } T_f = T_v = T_w \quad (28)$$

A historical survey of the radiation laws is to be found in reference (156).

## IV. THE MOST IMPORTANT AUXILIARY RADIATORS

### 1. *Introduction*

The purpose of measuring radiation is to study the radiation performance of any given radiator. For this, it is necessary to use auxiliary radiators.

One type is the comparison radiator, used when direct measurement is not possible. Another type is a radiation source for measuring the sensitivity of detectors and the transmission factors of filters. Line radiators are often used for the practical determination of wavelengths.

We shall now consider the most important auxiliary radiators, some of which are radiation sources which are really intended for quite different purposes.<sup>1,3,5,6,10,12,14,16</sup>

The first requirement of such a radiator is at the least constancy of emission over a short period of time. Regularly recurring fluctuations (as caused by alternating current), if their period is considerably shorter than the period of measurement, are of no great hindrance. Another important point is spatial constancy, i.e. spatial distribution of the radiation must not change with time. This is very important when optical images are part of the technique.

High radiant intensity per unit area (radiance) is advantageous as in most cases this is the decisive energy parameter. Naturally, the emission of the radiator should be as high as possible in the desired wavelength band.

As in most cases the radiator proper is enclosed in an envelope (e.g. the glass bulb of an electric lamp), care must be taken that the highest possible amount of radiation is transmitted through that envelope. For this reason, special glasses and quartz are used for ultra-violet and these also transmit in the near infra-red band. This does not apply to medium infra-red, because the radiators used for this region of the spectrum do not need an envelope. On the other hand, quartz has good transmission in the far infra-red.

The best dimensions for the radiating surface depend on the desired application. Often a rather large surface is desirable, while in other cases a point-like radiation source is necessary. The latter is particularly important when the inverse square law is assumed, since this is only valid for point-like sources. This means in practice that the dimensions of the radiator must be small compared with the distance of the receiver from the radiator. Sometimes it is an advantage if the radiating surfaces are as much as possible in one plane.

The last and most difficult requirement is reproducibility of the emission under constant conditions. A radiator which meets this condition can be used as a standard. Naturally, one should first determine the emission of such a standard radiator and check its constancy. Furthermore, when it is possible

to determine the emission exactly—by an appropriate choice of construction data or standardized specification, we can arrive at an official standard.

## 2. *Thermal radiators*

All thermal radiators have in common a strong dependency of the radiation on the temperature, which, in the case of a black body radiator, corresponds with the fourth power of the temperature (equation (24b)). In the case of other thermal radiators the situation is more complicated because the emissivity depends on the temperature.<sup>4</sup> As the energy supply is mostly electric, and as the heating effect of the current changes with the square of the current (at constant resistance) the radiator depends to a very large extent on the changes in current.

### (a) *Black body*

At the present moment, the only radiator with an exactly defined emission (which can also be calculated from theoretical relations) is the black body radiator. It can therefore be used as a standard of radiation. For any given temperature, the spectral concentration of radiant intensity depends only on the size of the radiant surface. The isotherms of Fig. 10 clearly show that a very high temperature of radiator must be chosen to obtain easily measurable quantities in the short-wave spectrum. Equally, the change of emission with temperature corresponds with a steep fall of the isotherms in the ultra-violet region. This imposes well-defined limits for practical use.

The highest temperatures used so far with the black body radiator are in the region of  $3,000^{\circ}\text{K}$ . A high current consumption is required.<sup>21,125,130</sup> For technical reasons it is therefore more usual to remain below  $2,000^{\circ}\text{K}$ , although ultra-violet emission, especially in the short UV band, is very small.

For radiation measurement, the black body radiator must emit easily measurable quantities of radiation, requiring a certain minimum area of the radiating surface. On the other hand, the value of the radiant aperture should be kept as small as possible in relation to the other dimensions, in order to ensure a close approximation of total radiation. With regard to the further conditions, such as heating of the radiator, keeping the temperature constant, etc., the most favourable solution has to be found.

The temperature can be satisfactorily kept constant by surrounding the radiant cavity with molten metal or vapour so as to operate at a fixed point, such as the boiling point of sulphur or melting point of gold. This at the same time ensures good constancy of temperature over the entire radiator. The physical dimensions of the radiant surface are naturally limited by the test conditions<sup>4,76,174</sup> (see Fig. 12).

Larger radiators are designed in cylindrical form and heated in a tubular



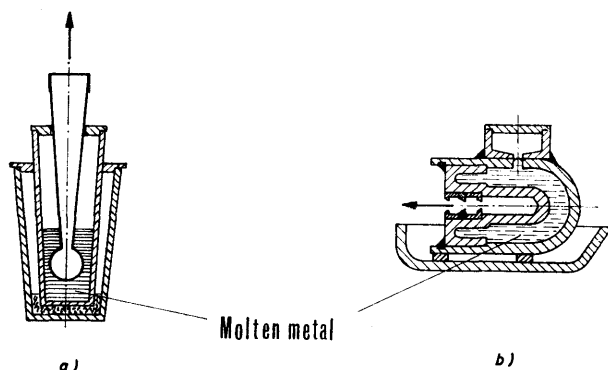


Fig. 12 Black body radiator: cavity enclosed by molten metal. (a) vertical arrangement (Hoffmann and Meissner<sup>78</sup>); (b) horizontal arrangement (Tingwaldt and Kunz<sup>174</sup>).

furnace or by induction. Temperature constancy is however more difficult to obtain<sup>108,110,124,181</sup> (see Fig. 13).

The "blackness" of the radiator, i.e. its emissivity, depends also on the degree of emission or absorption of the material of the cavity walls and can be computed or obtained by experiment. The walls are usually coated with a metal oxide, e.g. nickel, cobalt, iron or chrome oxide.<sup>30a,89,108,124,154,177,179</sup>

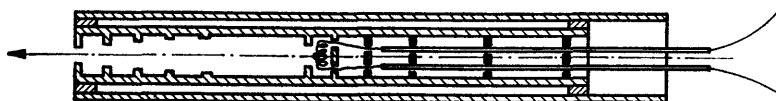


Fig. 13 Black body radiator: cavity in tubular furnace (Lummer and Kurlbaum<sup>108</sup>).

### (b) Incandescent lamp

The incandescent lamp is undoubtedly the most convenient thermal radiator and is used in various forms for measurement purposes. This lamp consists nowadays mostly of a tungsten filament—often coiled—in a vacuum or gas-filled bulb, heated by electric current. The light efficiency is small (about 5 per cent) but the radiation yield is considerably larger. The radiation emission becomes perceptible only in the long-wave UV band and reaches its maximum value in the near infra-red band, depending on the temperature of the tungsten filament.<sup>74,109,182</sup>

Great care must be taken to keep the lamp current constant in order to obtain constancy of emission. As a rule of thumb we can assume that the permissible percentage tolerance for the current is no more than one-tenth of the corresponding radiation tolerance. As in turn the radiation tolerance must be about one-tenth of the permissible error of the radiation measurement,

the following estimation can be used: When a radiation measurement with a tungsten lamp must be correct to 1 per cent, the radiation fluctuation must not exceed 0.1 per cent, which requires a current constancy of at least 0.01 per cent. Without special apparatus this is not possible.

Batteries provide the most convenient source of electric energy, provided that special variable resistors with good contacts (with low and very constant contact resistance) are used (see Fig. 14).

It is useful to determine the voltage and thereby the resistance of the filament lamp at the same time. When the voltage remains constant over long periods of time, one can be certain of a high degree of constancy of radiation. It is often not possible to do without compensators, in order to attain the required exactness (see Fig. 15).

It should be noted that through recrystallization and evaporation of the filament, deposits are sometimes formed on the inside of the lamps which impair the transmission through the glass envelope.

Also, in the far infra-red band, the radiation from the glass envelope cannot be neglected in comparison with the radiator element itself. The spatial dimension of the radiator is thereby increased.

Generally speaking, a filament lamp is used for the visible and near infra-red spectrum. The following requirements apply (see Figs 16 and 17):

Minimum-sized filament and small bulb, to approximate a point-like radiation source, should be used when the inverse square law is applied or a parallel beam is to be produced (e.g. headlamps).

Maximum radiant intensity per unit area is desirable when an image is to be formed on the slit of a spectroscope (e.g. projection lamps with coiled coils).

Maximum constancy over long periods of time when the lamp is used as a standard is obtained with a lamp filament in the form of individually suspended wires, sometimes arranged in a single plane (e.g. Osram Type Wi 40 lamp).

If a radiant surface of constant temperature is required, a tungsten ribbon lamp is used. These are also available with quartz window.

Generally speaking, the emission of vacuum lamps is more constant, but they cannot carry a heavy load without the filament evaporating. Gas-filled lamps are therefore better for higher temperatures.

It is an advantage that for tungsten—used almost exclusively in filament lamps—it is legitimate to specify the distribution temperature in the visible spectrum, which, according to what has been stated in Chapter III, is the same as the colour temperature.<sup>178</sup>

While in the middle of the visible spectrum the agreement with the spectral distribution of a black body is within about 0.5 per cent, much larger deviations appear at the limits of the visible spectrum. These deviations increase in both the ultra-violet and infra-red regions.

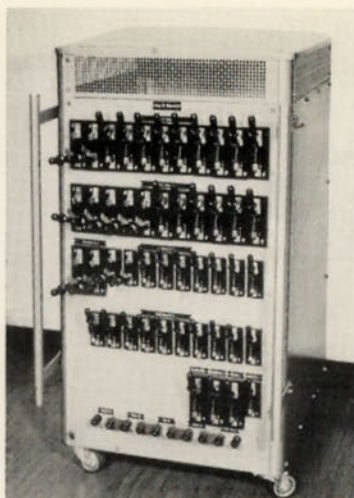
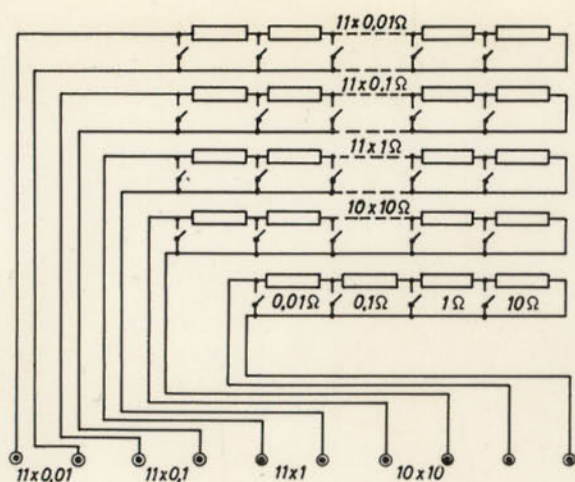
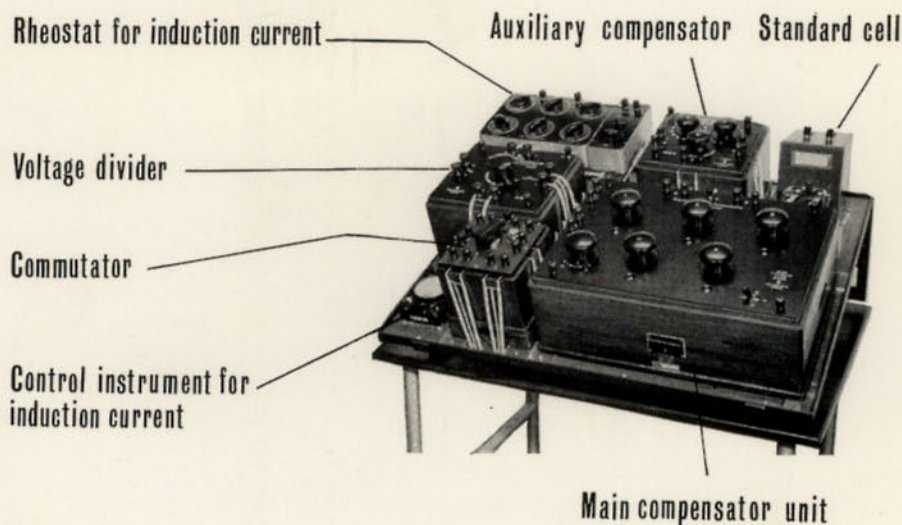


Fig. 14 High-load special resistor. Adjustment by shorting sub-resistors by means of knife switches. This ensures: (a) small contact resistances and therefore good current constancy; (b) by failure of a single switch, the circuit is not interrupted.

Fig. 15 Diesselhorst compensator for measuring D.C. tensions from  $10^{-8}$ – $10^2$  volts.



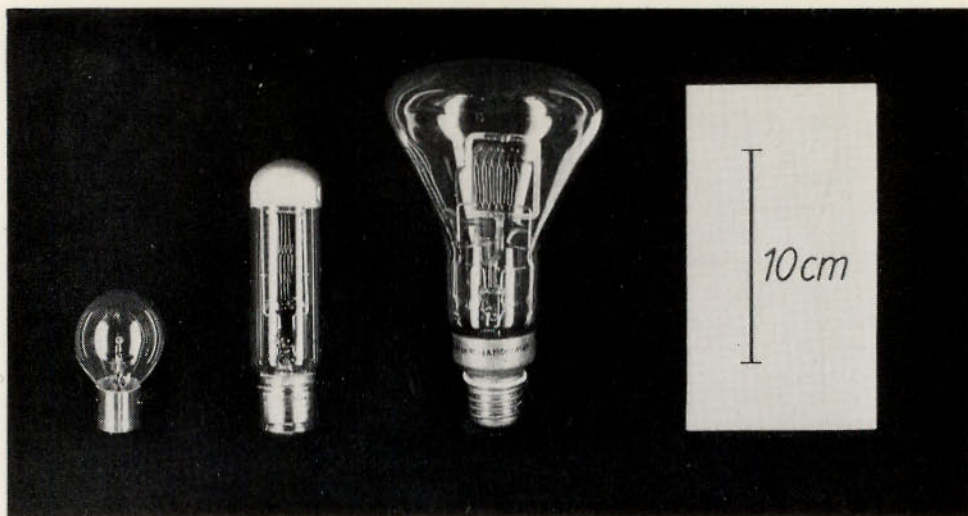
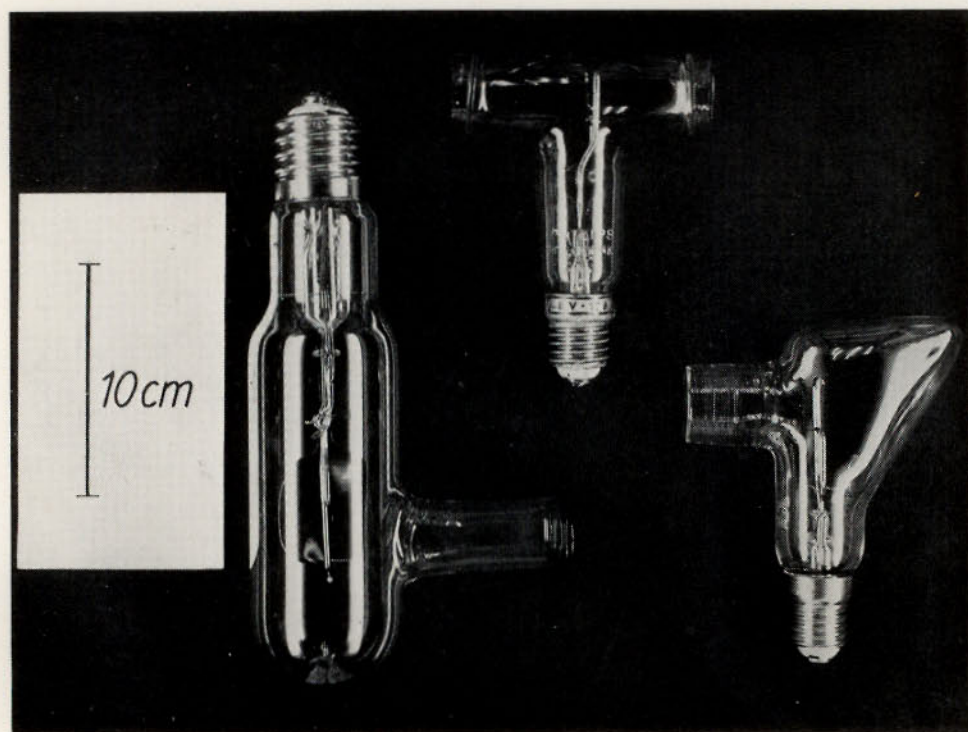


Fig. 16 Different types of filament lamps (Osram). (a) headlamp bulb; (b) projection lamp; (c) Wi 40 lamp.

Fig. 17 Tungsten ribbon lamps. (a) with cemented window (Osram); (b) with fused window (Philips).





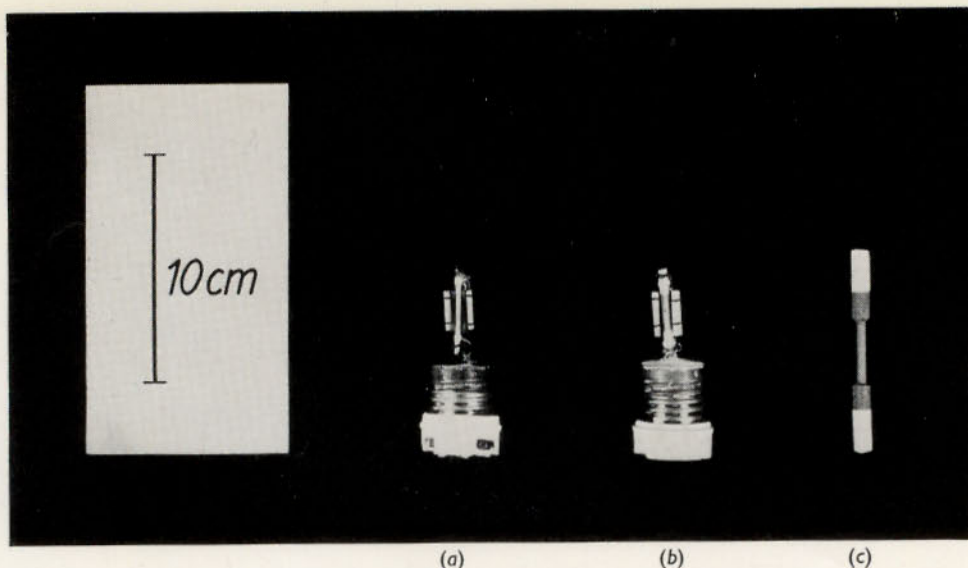


Fig. 18 Nernst lamp (a and b) and 'Globar' (c). The two illustrated Nernst lamps have additional heating rods on both sides of the central radiator; this ensures a larger zone of constant temperature.

Fig. 19 Monochromatic light lamps (Osram).

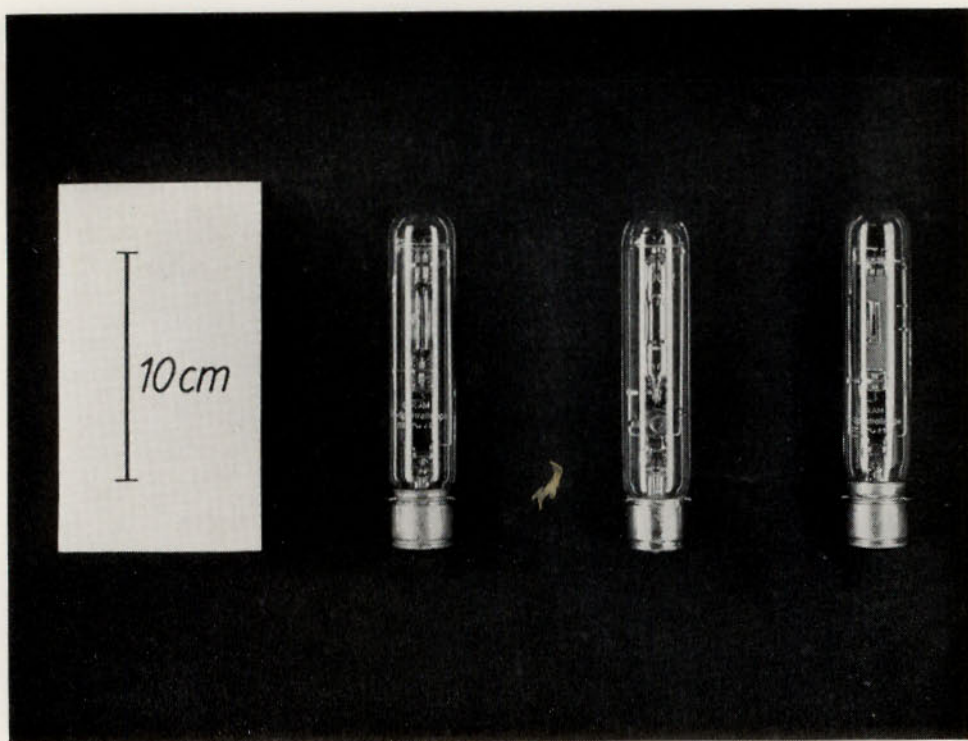


Fig. 20 Mercury low-pressure lamps.  
(a) Philips; (b) Osram; (c) Quarz-  
lampengesellschaft.

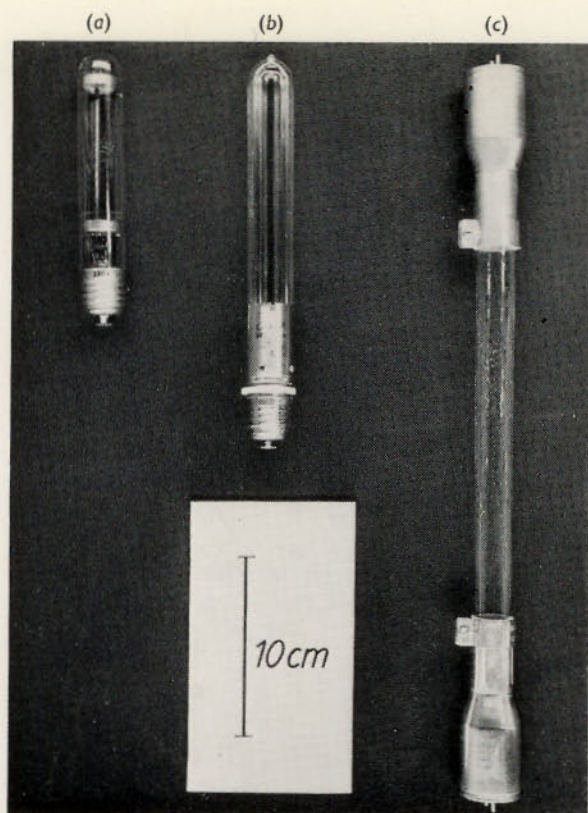
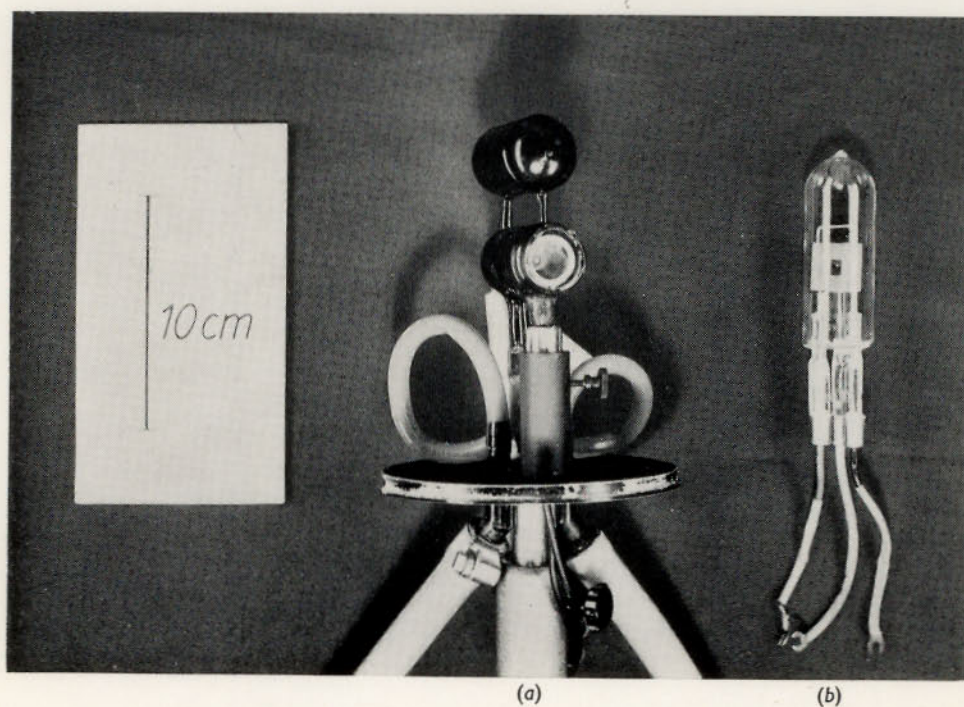


Fig. 21 Hydrogen lamps. (a) Kern  
und Sprenger; (b) Quarzlampen-  
gesellschaft.





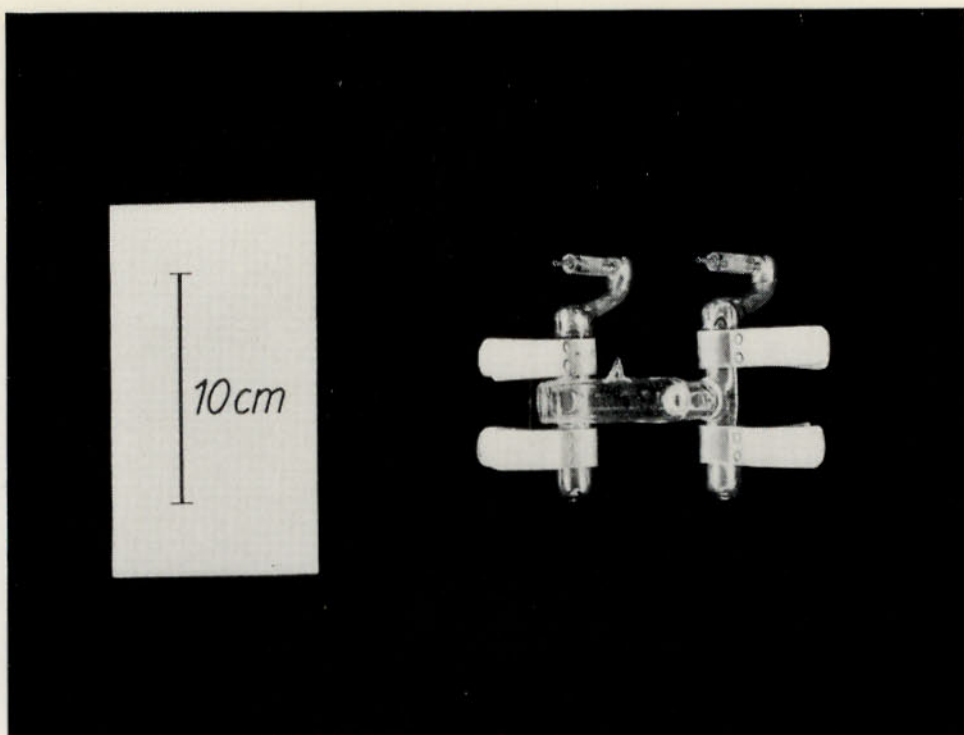
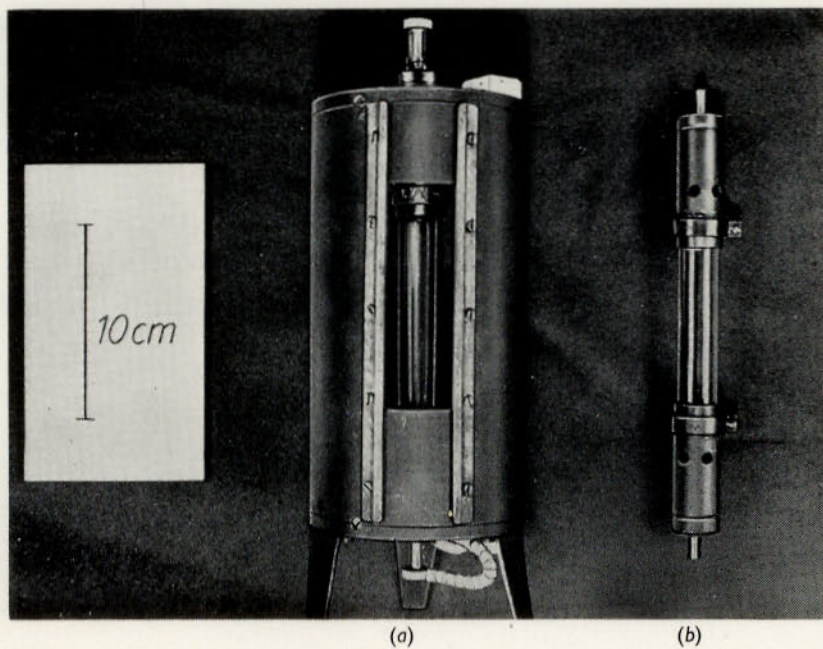
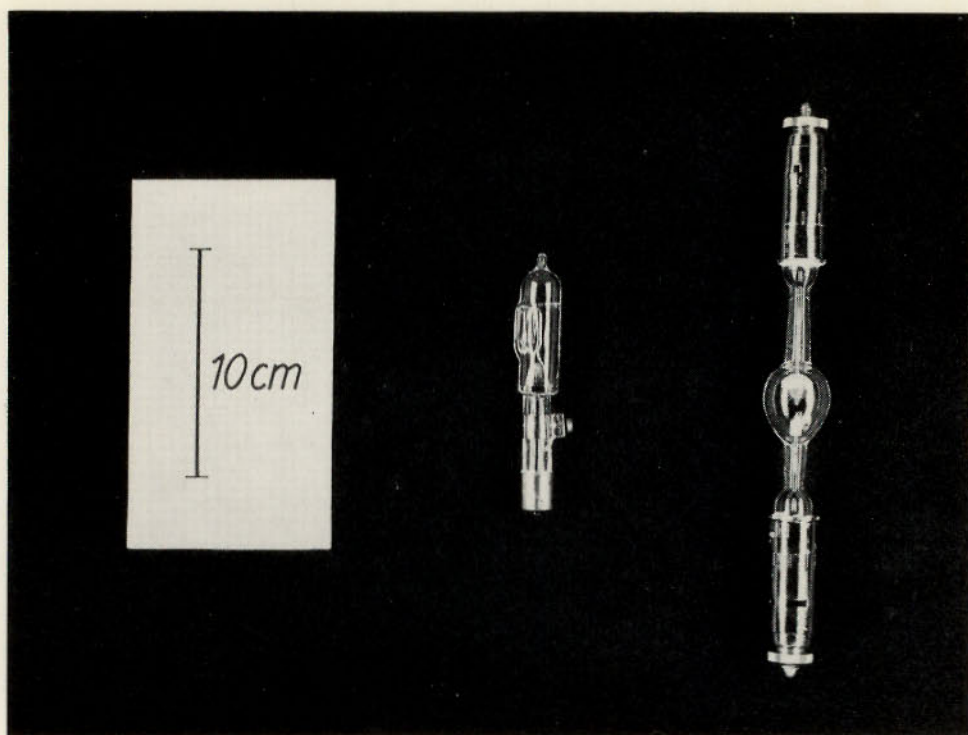


Fig. 22 Mercury vapour lamp with liquid electrodes.

Fig. 23 UV standard lamp (Osram). (a) in casing; (b) lamp.



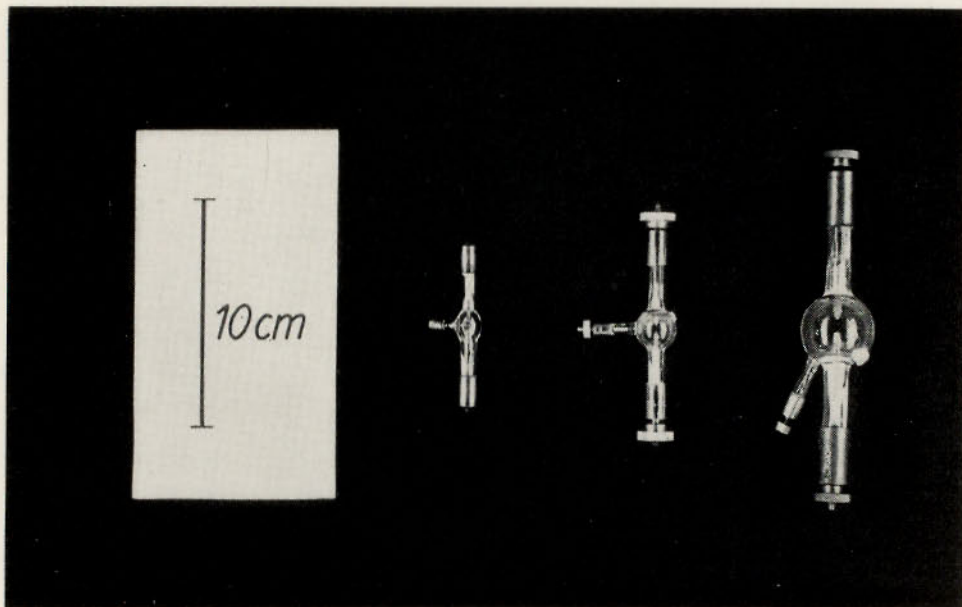


(a)

(b)

Fig. 24 Xenon high-pressure lamp (Osram). (a) high-pressure spectral lamp; (b) high-pressure lamp.

Fig. 25 Mercury very high-pressure lamps (Osram).



*Manufacturers: Philips; Osram.*

(c) Nernst lamp and 'Globar' sources

When it is impossible to use filament lamps in the infra-red band, the Nernst lamp<sup>173</sup> and lately the 'Globar'<sup>168</sup> are used because they do not require a glass envelope. They are pure thermal radiators requiring high constancy of operating current when constant radiation is the aim (see Fig. 18).

The Nernst lamp has a rod of material of 85 per cent zirconium oxide and 15 per cent yttrium oxide, heated by the passage of a current through it. The rod has a diameter of a few millimetres and a length of several centimetres; the required current is 1 amp at 110 volts.

*Manufacturer: Oskar Glaser; Hilger and Watts.*

The 'Globar' source is of similar dimensions but is made of silicon carbide. The required current is 5 amps at 50 volts.

*Manufacturer: Cesiwid G.m.b.H.*

Both types of lamps have a negative current-voltage curve, which makes it essential to use a current limiter (ballast resistor).

### 3. Gas discharge radiators

The second technically important way to produce radiation is by electrical excitation of gases or vapours.

In the absence of special arrangements a gas is not a conductor at atmospheric pressure. A gas becomes conductive between 1 and  $10^{-4}$  Torr, if a potential of a few hundred volts is applied. In this pressure region the free path is such that ionization by collision becomes possible. By further decreasing the pressure, the number of possible collisions becomes so small that ionization is rendered impossible, with resulting decrease in the conductivity. In this case too, a current limiter will be required in view of the negative current voltage characteristics.

By the recombination of the ions with electrons, radiation of the appropriate wavelengths will result, mainly the line spectrum of the gas concerned.

When special precautions are taken in the form of suitable gas or vapour combinations, electrode design, provision of a secondary electrode for ignition, ignition with secondary voltage, it is possible, even in the case of considerably higher pressures, to obtain a discharge through a gas or vapour. If the pressure is increased, a continuous spectrum will be superimposed on the line spectrum.

It is usual to term the pressure range between about  $10^{-4}$  and 1 Torr low pressure; between about 1 and 30 Torr high pressure; and over 30 Torr very high pressure.

Many gas discharge lamps, in particular the mercury discharge lamp, have a

considerable emission in the ultra-violet region. When intended for this region special glass or quartz is used for the envelope. The range of the spectrum itself depends on the specific gas or vapour used and other excitation conditions.<sup>114,190</sup>

The requirements of operating current and voltage stability are not so stringent as in the case of thermal radiators. The reason is that the radiation does not change as much with variations in the current supply. In most cases, an approximately linear connection between radiation characteristics and small changes in the electrical parameters may be assumed.

#### (a) Low-pressure lamps

The spectrum of a low-pressure discharge is of atoms and often consists of only a few lines and such lamps are used in all cases where monochromatic radiation is required. These discharge lamps are available as a series of spectrum lamps and serve as wavelength standards (see Fig. 19).

The mercury discharge lamp is characterized by the outstandingly strong emission of wavelength 254 m $\mu$  at very low pressure and low current intensity. These lamps have sterilizing properties and are often used for killing germs (Fig. 20).

#### (b) High-pressure lamps

The hydrogen lamp can be regarded as a high-pressure lamp; its radiation is important in the UV region.<sup>93,96</sup> At a pressure of a few Torr a discharge can pass through hydrogen and a continuous spectrum is produced, which penetrates

TABLE 2  
SPECTRAL RADIATION DISTRIBUTION OF THE UV STANDARD LAMP (RÖSSLER)  
IRRADIANCE AT A DISTANCE OF 1 METRE FOR LINE SPECTRUM

$\lambda$ m $\mu$	$E$ $\mu\text{w}/\text{cm}^2$	$\lambda$ m $\mu$	$E$ $\mu\text{w}/\text{cm}^2$	$\lambda$ m $\mu$	$E$ $\mu\text{w}/\text{cm}^2$
230.2	1.1	292.5	1.1	772.9	0.08
232.3	0.5	296.7	10.7	818.0	0.06
235.2	1.7	302.5	19.9	877.1	0.1
237.8	2.0	312.9	46.7	899.0	0.1
240.0	2.4	334.1	5.1	943.1	0.09
244.6	0.5	365.7	69.7	1014.0	23.8
246.4	0.6	390.6	0.6	1128.7	9.5
248.3	6.6	404.7	26.7	1188.7	1.8
253.7	*	407.8	4.0	1207.0	
257.6	1.1	435.8	50.5	1357.0	
260.3	0.4	491.6	0.7	1367.3	14.3
264.0	0.4	546.1	62.8	1395.1	
265.3	16.2	578.1	51.4	1691.8	
269.9	3.1	623.4	0.1	1693.9	
275.7	2.7	671.6	0.08	1710.8	11.9
280.4	7.1	690.7	0.6	1719.3	
289.4	4.1	708.7	0.2		

\* Self reversal (resonance line)

far into the ultra-violet region. The radiance is relatively small. This spectrum is the molecular spectrum of hydrogen; this makes it necessary to use special electrodes to ensure that the atomic hydrogen which is produced during the discharge can quickly combine to form molecules. Instead of ordinary hydrogen, heavy hydrogen (deuterium) is often used with resulting increase of radiance by 2 or 3 times. While in the past several thousand volts were required, modern lamps using hot cathodes are run at a voltage of about 100, the operating current being 0.3–1.5 amps (see Fig. 21).

The mercury vapour lamp with liquid electrodes used to be employed in laboratories. This lamp was ignited by tilting the entire unit, which proved inconvenient. Furthermore, the radiation was not sufficiently constant for radiation measurements (see Fig. 22).

A most convenient radiator is the UV standard lamp, developed by Krefft Rössler and Rüttenauer. This lamp operates with mercury vapour at about 1.5 atmospheres and has a very constant emission, which recommends its use as a standard lamp. The absolute values of the emission nevertheless show slight changes between individual lamps made under standardized manufacturing conditions. On the other hand, the relative spectral distributions agree very well. The radiant intensity per unit area is high; higher than that of the mercury spectral lamp<sup>147,150</sup> (see Fig. 23, Tables 2 and 3).

TABLE 3  
SPECTRAL RADIATION DISTRIBUTION OF THE UV STANDARD LAMP (RÖSSLER)  
IRRADIANCE AT A DISTANCE OF 1 METRE FOR CONTINUOUS SPECTRUM

$\lambda$ m $\mu$	$E_\lambda$ $\mu\text{w}/\text{cm}^2\text{m}\mu$	$\lambda$ m $\mu$	$E_\lambda$ $\mu\text{w}/\text{cm}^2\text{m}\mu$	$\lambda$ m $\mu$	$E_\lambda$ $\mu\text{w}/\text{cm}^2\text{m}\mu$
200.0	0.00	280	0.26	550	0.05
205.0	0.00	285	0.25	580	0.05
210.0	0.03	290	0.26	600	0.04
215.0	0.19	295	0.27	700	0.04
220.0	0.42	300	0.29	800	0.04
225.0	0.56	310	0.33	900	0.03
230.0	0.59	320	0.36	1,000	0.03
235.0	0.54	330	0.37	1,500	0.03
240.0	0.49	340	0.32	2,000	0.04
245.0	0.44	350	0.25	2,500	0.06
250.0	0.38	360	0.18	3,000	0.07
253.4	15.08	370	0.12	3,500	0.08
255.0	7.77	380	0.09	4,000	0.15
260.0	1.67	390	0.07	4,500	0.21
265.0	0.85	400	0.07	5,000	0.18
270.0	0.43	450	0.05	5,500	0.14
275.0	0.30	500	0.04	6,000	0.11

Remarkably enough, the UV standard lamp also shows a perceptible emission in the far infra-red, which enables measurements to be made in the region adjoining the millimetre waves.<sup>31,151</sup>

Xenon high-pressure lamps are at the other end of the range of discharge lamps.<sup>22,101,102,160</sup> They are available in different forms. All Xenon lamps are characterized by a very long continuous spectrum which closely resembles sunlight in the visible region.

With lamps of particularly high radiance and with a very compact radiating area, any wandering of the discharge can have disturbing results, especially when working with images.

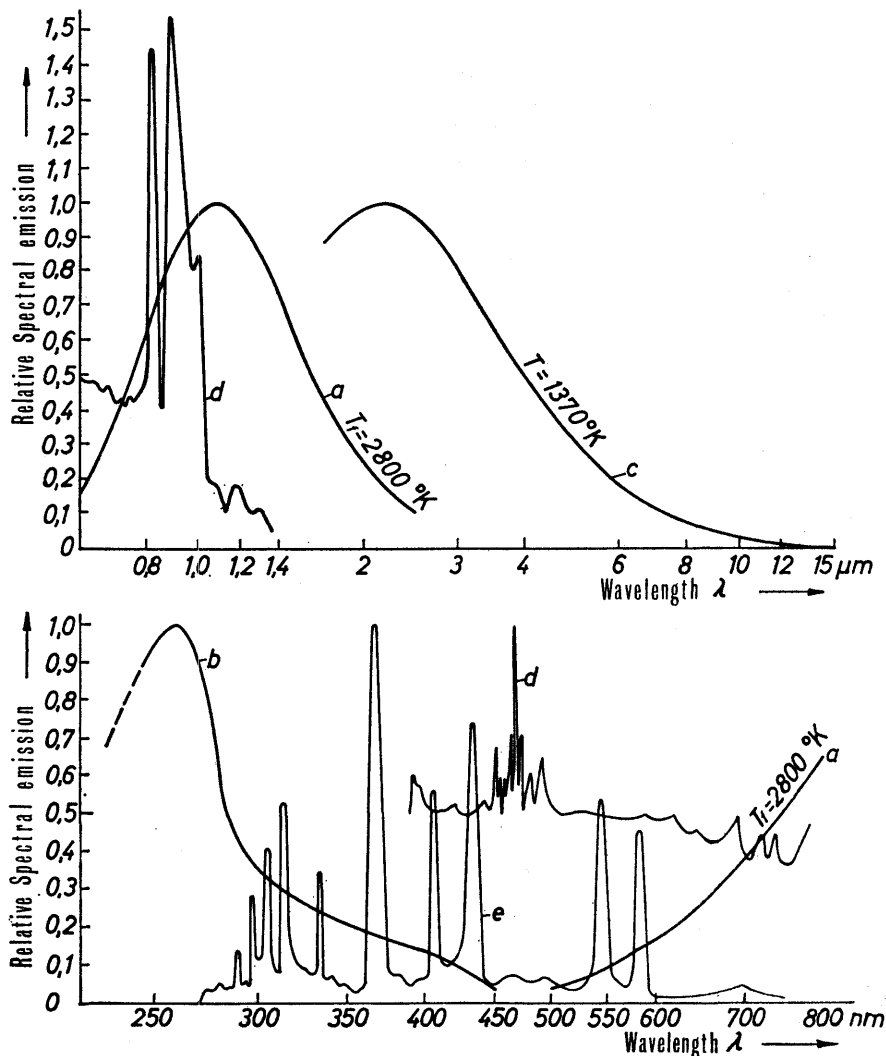


Fig. 26 Relative spectral radiation distribution of different radiators. (a) tungsten strip lamp; (b) hydrogen lamp; (c) 'Globar'; (d) xenon high-pressure lamp; (e) mercury high-pressure lamp.



This drawback is avoided in a xenon high-pressure lamp specially designed for radiation physics. Here the discharge is forced to pass through a groove in the tube.<sup>24,73</sup> The intensity of this lamp is not as high as in the case of other lamps (see Fig. 24).

(c) Very high-pressure lamps

The most important of these is the mercury high-pressure lamp.<sup>45,46,59</sup> The radiation consists of a continuous spectrum with superimposed broad lines which commence in the ultra-violet and extend far into the infra-red. The area occupied by the discharge is mostly small, so that wandering of the discharge can cause difficulty (see Fig. 25).

*Manufacturers: A.E.I.; G.E.C.; Hanovia; Hilger and Watts; Kern and Sprenger; Osram; Philips; Quarzlampengesellschaft m.b.H.; Siemens.*

#### 4. Arc and spark discharges

The arc discharge, mostly with carbon or graphite electrodes, is sometimes used for measurements.<sup>47,48</sup> When certain precautions are observed, the emission is determined by the operating conditions, so that the arc can be used as a radiation standard. Unfortunately, the precision with which the emission can be expressed is rather doubtful. For this reason and because of the inconvenience of having to regulate the electrodes, the arc lamp is rarely used as a radiation standard.

Spark discharges are hardly ever used for measurement purposes because of the lack of constancy over a period of time and the lack of reproducibility.

The relative distribution of different radiators is shown in Fig. 26.

## V. SPECTRAL ANALYSIS

### 1. *Scope of spectral analysis*

In practice we always have to deal with a mixed radiation consisting of different wavelength bands. On one hand we are interested in the spectral composition of the radiation itself; on the other hand, monochromatic radiation is required for many purposes. This requires the separation of the individual wavelength bands of a mixed radiation, namely spectral analysis.

Basically, all radiation characteristics which depend on the wavelength can be employed to this end; refraction, interference, absorption and reflection.<sup>1,4,5,6,12,13,14,16</sup>

#### (a) Refraction

Because refraction primarily depends on wavelength, a phenomenon called dispersion, a mixed radiation passing through a prism, will be found to undergo direction changes of different magnitudes related to the wavelengths in the radiation. A fan-like deployment results. The materials used for making the prism must possess sufficient transmission required for the desired wavelength band (see Fig. 27) and sufficient dispersion\* (Fig. 28).

According to the wavelength band, the following materials are used:

Glass	from about 0.35 $\mu$ to about 2.5 $\mu$	
Quartz glass	0.22	3.5 absorption at 0.24 and 2.75 $\mu$
Quartz crystal (SiO <sub>2</sub> )	0.2	3.8 absorption at 2.9 $\mu$
Fluorite (CaF <sub>2</sub> )	0.2	9
Lithium fluoride (LiF)	0.5	6 absorption at 2.8 $\mu$
Rock salt (NaCl)	0.2	17 hygroscopic
Sylvite (KCl)	0.2	20 hygroscopic
KRS 5 (44% TlBr + 56% TlI)	1	35 very soft

For the far infra-red region, KBr, CsBr and CsI have been used lately.

#### (b) Interference

When a mixed radiation is incident on a grating, a distribution of intensity will be observed in the reflected or transmitted radiation, caused by interference, dependent on the direction and wavelength of the radiation. A certain

\* See equation (31).

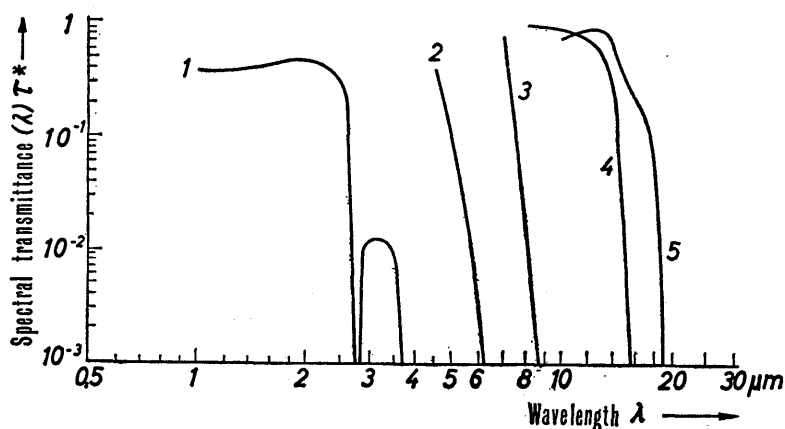


Fig. 27 Long-wave boundary of the degree of spectral transmission of prism materials (optical path 10 cm):  
 ①  $\text{SiO}_2$  ②  $\text{LiF}$  ③  $\text{CaF}_2$  ④  $\text{NaCl}$  ⑤  $\text{KCl}$

direction is not only characteristic for a single wavelength but also for all whole-number multiples of that wavelength. For the same reason, there is also a whole range of directions, called "orders" for a given wavelength, in which intensity maxima occur. An additional separation, which may be by means of a filter, is therefore required. Furthermore, the radiation flux is often spread into several orders, each of which is therefore of relatively low intensity. This can be improved by using a special form of reflection grating, in which a chosen direction of reflection is favoured. Such gratings are called echelon gratings (see Fig. 29).

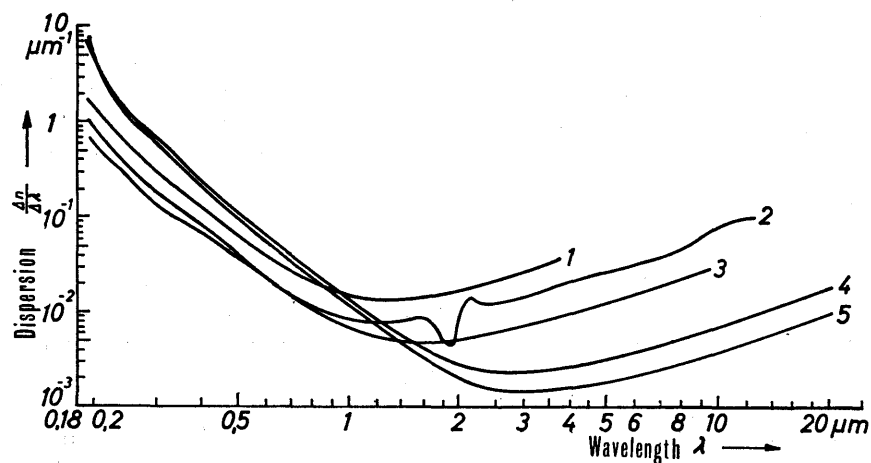


Fig. 28 Dispersion of prism materials<sup>4</sup>:  
 ①  $\text{SiO}_2$  ②  $\text{LiF}$  ③  $\text{CaF}_2$  ④  $\text{NaCl}$  ⑤  $\text{KCl}$

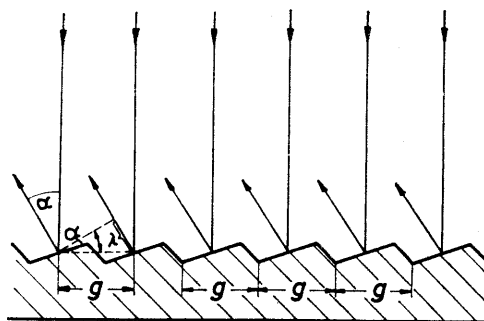


Fig. 29 Echelon grating.

$g$  = grating constant; first order spectrum for  $\lambda = g \sin \alpha$

Interference filters are based on the phenomenon of interference in a different way. They consist of a support (mostly glass) on which are deposited several very thin layers of different optical properties. By interference of the transmitted radiation and of the radiation reflected in the layers, such a filter can be made to transmit only within very narrow limits of wavelength. Half-width values of  $5 \text{ m}\mu$  can thus be obtained at a degree of transmission of 20–30 per cent. At the present time, filters are available for ultra-violet and visible radiation, as well as for the near infra-red band. It should be noted that higher-order transmission can occur which can be eliminated by the use of additional filters (see Fig. 30).

#### (c) Absorption and reflection

It often occurs that solid, fluid or gaseous substances only transmit radiation in a few wavelength bands or even a single one. In general, these transmission bands are quite wide (see Fig. 31).

In principle, this process can also be used for reflected radiation. This application has gained importance in the method of "Reststrahlen," particularly in the far infra-red where metallic reflection in limited wavelength bands occurs, even in the case of non-metals. The well-reflected spectral region is cleanly separated by multiple reflection.

#### (d) Comparison of different methods

The favoured method for the analysis of radiant energy from the ultra-violet to medium-wave infra-red is by means of a prism. This method yields a relatively large radiation flux, offers a sufficiently large resolution by choosing a suitable substance for the prism and allows the selection of radiation of any specific wavelength within the spectral region concerned.

There are, however, no suitable dispersing substances for the far infra-red, so that recourse to gratings becomes necessary. The latter have so far only rarely been used for short-wave regions, because of the superimposition of the

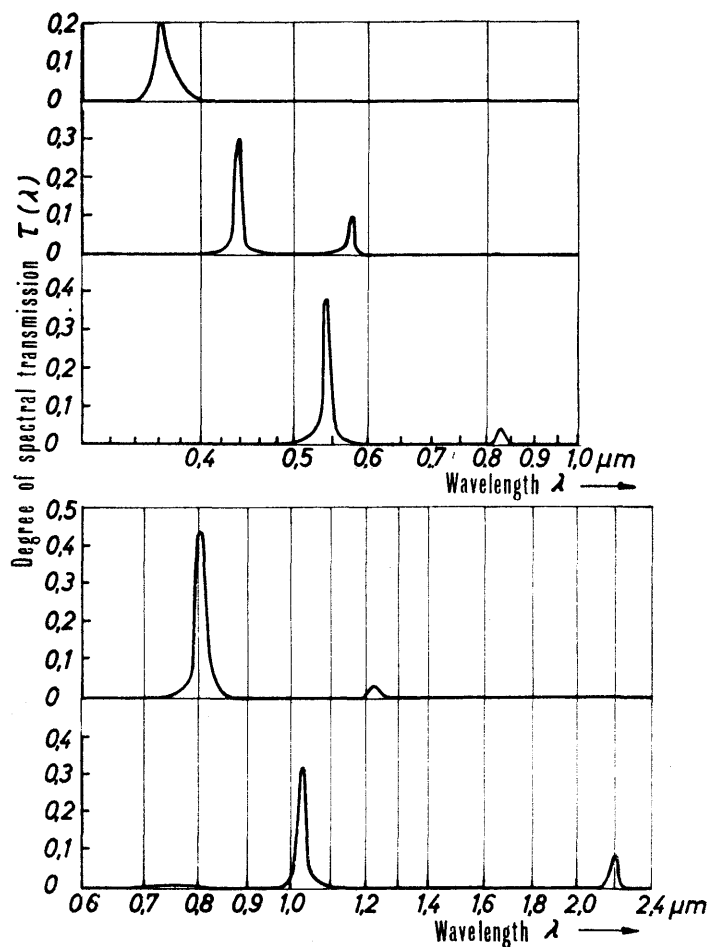


Fig. 30 Transmission of interference filters.

different orders and the relatively low transmission factors. Recent development in echelon grating technique, however, seems to indicate a definite improvement in this respect.

The use of filters for spectral measurement has lately become more widely spread, particularly because sufficiently selective interference filters are now available. Filters score over the usual spectral apparatus because of their greater aperture and often higher transmission factor. On the other hand, several filters must be used when a somewhat fine subdivision of wavelengths is desired. Neither are there facilities for an easy adjustment of the wavelength. Exceptions are the graduated interference filters; their applications are however restricted.

Disregarding the concave grating, which is ruled on the surface of a concave spherical mirror and is capable of focusing the radiation without other optical means, the basic components of a grating device are the same as those of a prism device. In fact, there exist instruments where the grating and prism are interchangeable.

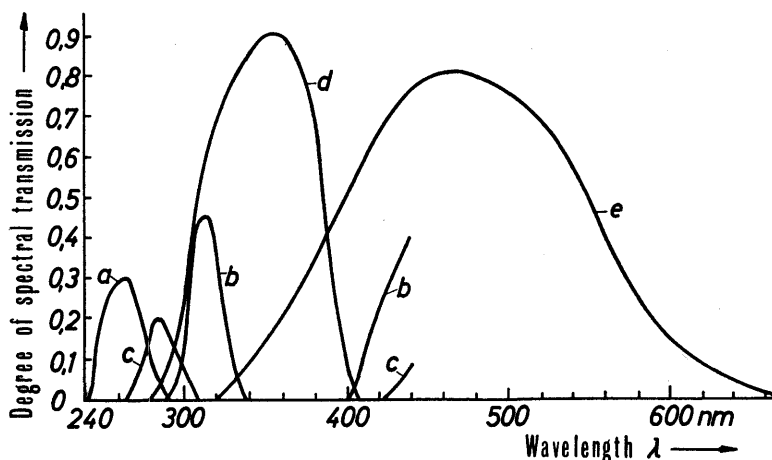


Fig. 31 Spectral transmission of different substances. (a) chlorine-bromine mixture, 50 mm; (b) potassium chromate, 10 mm; (c) picric acid, 10 mm; (d) Schott filter UG2, 1 mm; (e) Schott filter BG7, 1 mm.

It will therefore suffice to discuss the prism devices in more detail, as they are more frequently used.

It should be noted that in all these methods the monochromatic radiation may be polarized to a greater or lesser extent.

## 2. Spectroscope and spectrograph

The spectroscope is an instrument for the visual observation of spectra. A spectrograph is the same instrument when fitted with a recording device, most often photographic in nature.<sup>66,115</sup>

A finely adjustable slit is always used for spectral analysis (height 1–10 mm, width 0.01–5 mm) and is illuminated by the radiator to be examined. For maximum illumination, an image of the radiator is often formed on the slit. One can give a certain radiance to this slit image which can be considered as being uniform for the entire slit area.

The slit is placed in the focal plane of a collimating lens, which produces a parallel pencil of rays. The latter then falls on a prism, disposed symmetrically



about the incoming and outgoing pencils to obtain maximum purity. The spectrograph has a photographic lens for recording the resulting spectrum.

After passing through the prism, the direction of the parallel pencil of rays becomes different for each wavelength, with the result that the images of the slit corresponding with different wavelengths stand in a row. According to the correction for chromatic aberration of the photographic lens, its focal length will depend on the different wavelengths, so that the slit images are not only fanned out but can also be sharpest at different distances from the lens. This is particularly the case with UV radiation for which the lens is never chromatically corrected. The slit images of the different wavelengths lie therefore on a curved focal surface (see Fig. 32).

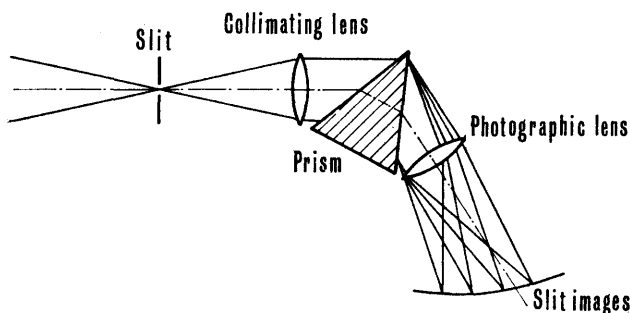


Fig. 32 Path of rays in a spectrograph.

Image formation by means of lenses, which is usual with spectrographs, has been assumed. Image formation can also be achieved by means of concave mirrors, which have the advantage of being free from chromatic aberration.

The depicted image formation relations only apply for a single point on the optical axis: the centre of the slit. All other points are subject to a slightly different dispersion through the prism, so that their images will be slightly displaced compared with the central point. The image of a straight line is therefore slightly curved. This can be compensated by using a curved slit, but strictly speaking this is only possible for a single wavelength.

When the positions of the slit images (produced by monochromatic radiation and very small slit width) are plotted against the wavelengths, a dispersion curve is obtained (see Fig. 33).

This dispersion can be represented by Hartmann's equation:<sup>4</sup>

$$\lambda = \lambda_0 + u/(v - b) \quad (29)$$

where  $b$  = position coordinate;

$\lambda_0$  = wavelength referred to;

$u$  and  $v$  = constants which must be determined experimentally.

For the plotting of dispersion curves, special graph paper can be used; whereby the dispersion curve becomes a straight line. The dispersion curve is determined by means of spectral lines or absorption positions of known wavelength. Sometimes use is made of interference fringes through

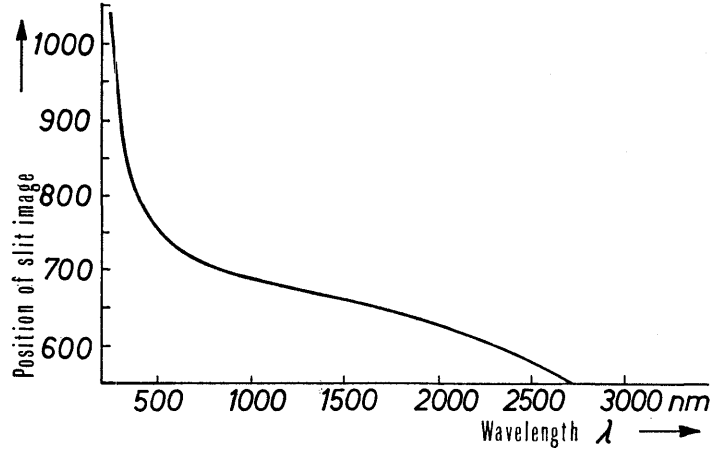


Fig. 33 Dispersion curve of quartz.

a pair of plane-parallel, half-silvered glass plates (Fabry and Perot interferometer).<sup>4,42,100,113,137,140,142</sup>

The (linear) dispersion  $D$  of the spectrograph is defined by:

$$D = db/d\lambda \quad (30)$$

and varies throughout the prismatic spectrum.

This value is of course the slope of the dispersion curve  $b$  as a function of  $\lambda$ , approximated to by Hartmann's formula and which is determined by the refractive index,  $n$ , of the prism, the focal length of the camera lens and the dispersion  $D^*$  of the material of the prism, best calculated for our purposes by

$$D^* = dn/d\lambda \quad (31)$$

The resolving power  $\lambda/d\lambda$  where  $d\lambda$  is the minimum recognizable wavelength separation in the spectrum is also important. It can be expressed as a function of the dispersion  $D^*$  and the prism base  $l$ :

$$\lambda/d\lambda = lD^* \quad (32)$$

The resolving power of a grating is:

$$\lambda/d\lambda = mN \quad (33)$$

where  $m$  = total number of lines in the grating;

$N$  = order of interference.

The width of a spectral line is so small except in high-dispersion spectrographs that it is of no consequence for the kind of work discussed in this book. The source can therefore be regarded as monochromatic and the width of the slit image is determined only by the size of the slit and the optical magnification in the spectroscope or spectrograph. When the slit is made wider, the radiant flux will, of course, be greater, but the width of the slit image will increase accordingly. The radiation is therefore distributed over a larger area and the radiant intensity remains constant.

In the case of a continuous spectrum, the overlapping of adjacent slit images will increase when the slit (and therefore the width of each individual image) is made wider. The radiant intensity will therefore increase.

In a mixed spectrum (line and continuous) the radiant intensity of the continuous spectrum will become greater by increasing slit width, while the intensity of the line spectrum will remain unchanged.

In order to separate the two parts, both slit width and dispersion must be taken into account. This will be dealt with later on.

In a spectrograph the sensitive layer of the photographic material must be in the surface occupied by the slit images. In the latest instruments this focal surface is usually flat, but in older ones frequently quite strongly curved. If plates are used they must be of thin glass. The photographic emulsion can be replaced by a ground-glass screen for visual observation. By treating this screen with a fluorescent material, it can also be used for observing ultra-violet radiation.

Instead of using photographic recording, a radiation detector could be traversed through the entire spectrum. Such an arrangement, however, has not met with success.

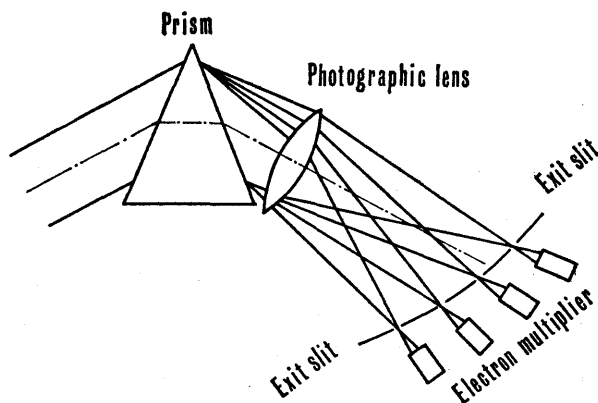


Fig. 34 Quantometer.

However, in recent times, radiation detectors have been arranged in fixed positions at appropriate points in the spectrum. Electron multipliers are used for this purpose. For spectrographic analysis of metals for example the chosen points would be those where standard lines and important impurity lines occurred. At each of these points an "exit slit" is arranged through which the light of the line which falls on it passes through to the multiplier. This arrangement is called a "quantometer" (see Fig. 34) and affords an easy and quick measurement of several spectrum lines simultaneously.

*Manufacturers: R. Fuess; Steinheil Söhne G.m.b.H.; Carl Zeiss, Oberkochen; Hilger and Watts.*

### 3. Monochromator

For measuring with a radiation receiver the most efficient method is to arrange the exit slit in a fixed position and to move the spectrum over the slit by rotating the prism. Such an instrument is called a "monochromator."<sup>36, 71, 103, 106, 129, 149</sup>

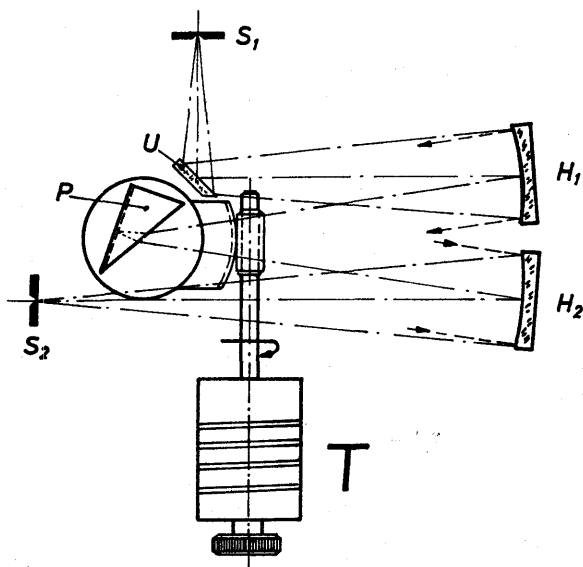


Fig. 35 Single-monochromator (Leiss).  $S_1$  = entrance slit;  $S_2$  = exit slit;  $H_1, H_2$  = concave mirrors; T = wavelength drum; U = mirror; P = prism.

The back of the prism is silvered so that the pencil of rays pass through the prism twice.

The entrance slit is thus imaged through a rotatable prism or grating on to a rigid outlet slit which isolates a wavelength band whose width depends on the dispersion and the slit width (see Fig. 35).

After a single spectral dispersion, part radiation, as a result of unavoidable internal reflections in the instrument, is superimposed on the spectrum. This

superimposed part is everywhere of more or less the same spectral composition as that from the source and is called "scattered radiation."<sup>41,92,139,169</sup>

Scattered radiation can be very much reduced by arranging a further similar spectral dispersion. The exit slit of the first dispersing unit acts as the entrance slit of the second. The latter slit then becomes the central slit. A monochromator with double dispersion of this kind is called a "double monochromator" to distinguish it from the single monochromator (see Fig. 36).

Walsh<sup>62,70,180</sup> succeeded by mechanical ingenuity in achieving multiple spectral dispersion with a single prism. He did this by reflecting the emerging ray and letting it pass once more through the prism. This arrangement, however, requires auxiliary devices which it is not proposed to describe in detail.

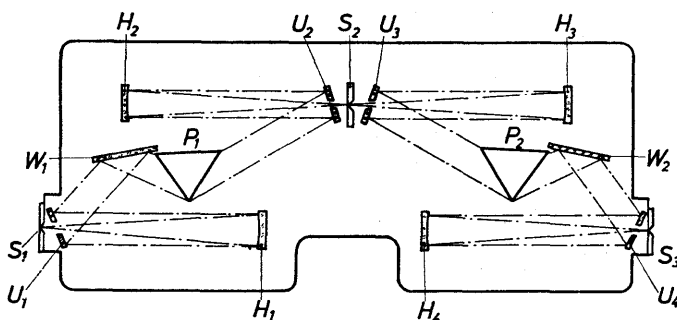


Fig. 36 Double monochromator (Kip en Zonen).  $S_1$  = entrance slit;  $S_2$  = central slit;  $S_3$  = exit slit;  $U_1, U_2, U_3, U_4$  = mirrors with central apertures;  $H_1, H_2, H_3, H_4$  = concave mirrors;  $W_1, W_2$  = Wadsworth mirrors (cf. Fig. 39);  $P_1, P_2$  = prisms.

Normally, the second dispersion in a double monochromator is arranged in such a way that it works in the same direction as the first dispersion. The band-width of the radiation emerging from the exit slit is then further reduced and the radiation is still more nearly monochromatic. In the case of a continuous spectrum, the second dispersion results in this case in a decrease in flux.

If the second dispersion occurs in the opposite direction from the first as it is made to do in some instances, the spectrum from which the required radiation is selected by the central slit, is reunited to a single white image at the exit slit.

This method has the disadvantage of not having further spectral dispersion of the wavelength band isolated by the central slit. Its advantage, however, consists in the elimination of scattered radiation without reduction of the flux passing through the exit slit when the spectrum is continuous. This means, apart from unavoidable absorption and reflection losses because of additional mirrors and lenses, the same radiance in the exit slit as the corresponding single monochromator.

By removing the central slit, the same radiation is again obtained apart from absorption and reflection losses, as at the entrance slit. On the other hand, if an aperture is arranged to replace the central slit, entirely or partly eliminating parts of the spectrum formed there, the radiation in the outlet slit will also be affected. This gives us the opportunity of altering the original spectral composition at will by a kind of mechanical filter.

To be completely free from chromatic aberration, especially in the ultra-violet and infra-red, concave mirrors are used for image formation in mono-

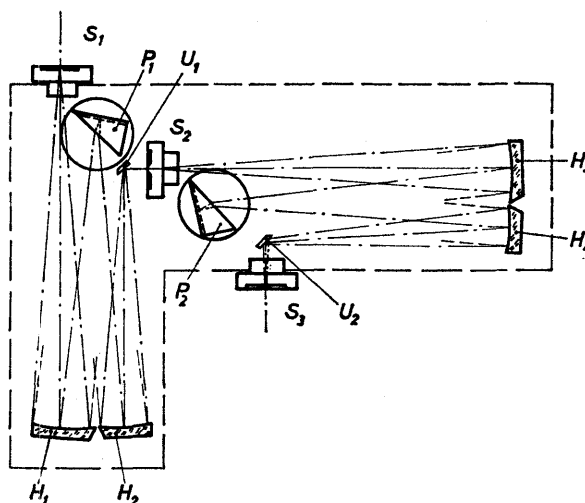


Fig. 37 Double monochromator (by Dr. Leo, Leiss).  $S_1$  = entrance slit;  $S_2$  = central slit;  $S_3$  = exit slit;  $U_1, U_2$  = mirrors;  $H_1, H_2, H_3, H_4$  = concave mirrors;  $P_1, P_2$  = prisms.

The back of each prism is silvered to ensure a double passage of the pencil of rays through it. Transverse aberrations occur in the opposite sense and are made of the same numerical magnitude by suitable choice of the focal lengths of mirrors  $H_3$  and  $H_4$ . This has the effect of annulling coma and similar aberrations practically completely.

chromators. As is known, optimum reproduction is obtained with concave mirrors when the radiation is parallel to the optical axis. Under these circumstances, a loss of radiation is unavoidable because of the use of extra mirrors for changing the directions of beam of light and central apertures in the concave mirrors. For this reason, in general, one uses oblique incidence on the concave mirrors and puts up with the disadvantage of greater aberrations, in particular greater coma. However, by proper dispositions in the two halves of a double monochromator, it is possible to correct these image aberrations to a very great extent<sup>43,105,134</sup> (see Fig. 37).

Finally, it is important that the beam of radiation passes through the prism in a symmetrical manner. This is the same condition as that which prescribes working with minimum deviation, for then the most favourable conditions

for spectral purity are created. Often it is only possible to approximate this condition, but artifices are possible to keep the deviation at the minimum.

Wadsworth for example uses a plane mirror forming a unit with the rotatable prism to guide the radiation to the prism. The design consists in fixing the plane mirror permanently parallel to the base of the prism, while the prism rotates. When the combination of prism and mirror is rotated, the angle of incidence of the beam of rays on the mirror will be altered and the direction of the reflected pencil of rays (which enters the prism) with respect to the prism will change by the same amount and so also will the beam leaving the prism. The effect is that, when the prism is rotated, the direction of the emerging beam remains unchanged for the wavelength which passes through the prism at minimum deviation. The relative positions of the mirrors, prism and pivot point are determined by the sole requirement that radiation loss is kept to the minimum (see Fig. 38).

As already mentioned, the prism may be substituted by a grating without any *fundamental* change in design.

*All that has been said about dispersion, dispersion curves and transmission factors when discussing the spectrograph, is also valid for the monochromator.*

For plotting the dispersion curve of a monochromator, however, the angular rotation  $s$  of the prism (indicated on the corresponding rotating device, e.g. drum  $T$  in Fig. 35) must be taken into account. The reason for this is that for every position of the prism, when the slit is very narrow, a corresponding wavelength will appear in the exit slit. The linear dispersion can then be expressed by:

$$D = db/d\lambda = (db/ds)(ds/d\lambda) \quad (30a)$$

With a single dispersion system using a very narrow entrance slit and a larger slit width  $b$  for the exit slit, the latter will cover a certain wavelength interval according to the width. The exit slit isolates a sharply defined portion

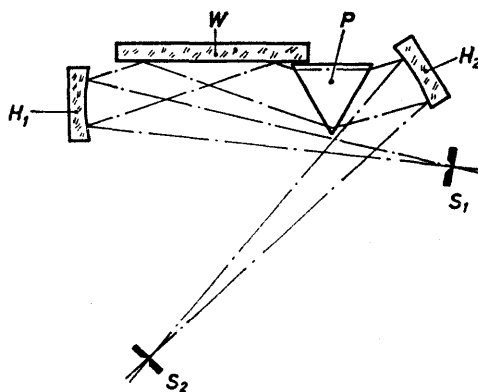


Fig. 38 Wadsworth arrangement.  $S_1$  = entrance slit;  $S_2$  = exit slit;  $W$  = Wadsworth mirror;  $H_1, H_2$  = concave mirrors;  $P$  = prism. The rays always pass through with minimum deviation.



of the spectrum and every narrow band within the exit slit corresponds to a different wavelength. We find therefore that for the wavelength interval  $\beta$ :

$$\beta = b/D \quad (30b)$$

In practice it is not possible for energy considerations to make the entrance slit of the monochromator as narrow as one would like. It is therefore best to keep the exit slit of the same width. If a continuous spectrum falls on the entrance slit, the isolated portion of the spectrum in the exit slit (to which a

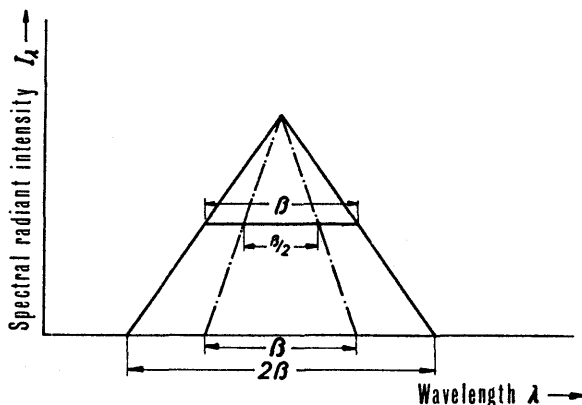


Fig. 39 Spectral radiation distribution in the exit slit of a monochromator. All slits have the same width. ——— simple dispersion; . — . — . — double dispersion.

mean wavelength can be accorded) shows a spectral radiation distribution which, on plotting, gives a triangle. The half-width value of this distribution, corresponding to the central parallel of the triangle, we speak of as the spectral slit width, which is the same as the wavelength interval  $\beta$  defined in equation (30b).<sup>28,148</sup>

By double dispersion in the same direction, the spectral slit width only amounts to  $\beta/2$ , provided that the central slit has the same width as the entrance or exit slit. Double dispersion not only contributes to the avoidance of scattered radiation, it also reduces the effective slit-width (see Fig. 39).

The sensitivity of the receiver may also depend on the wavelength. This must be taken into account for very exact measurements. A reduction to an infinitely narrow slit<sup>195</sup> should be carried out. In ordinary practice, this extremely cumbersome process can however be omitted.

*Manufacturers: Barr & Stroud; Perkin Elmer; Hilger & Watts; Kip en Zonen; Optica United Kingdom; Sir Howard Grubb Parsons; Carl Zeiss, Oberkochen.*

#### 4. Filters

Progress in the manufacture of coloured glasses and interference filters has in recent times greatly increased the importance of filters for monochromatic radiation measurements.<sup>119,163</sup> In this connection, the development of strong continuous radiators is also of importance, e.g. the xenon high-pressure lamp.

When the combinations of coloured glasses (liquids and gases are also sometimes employed for filtering) are used which are called "monochromatic filters," the transmitted wavelength region is always relatively wide. Good monochromatization is therefore obtained only in conjunction with a line radiator, which also produces sufficient radiation flux<sup>4,6,50,133</sup> (see Fig. 40).

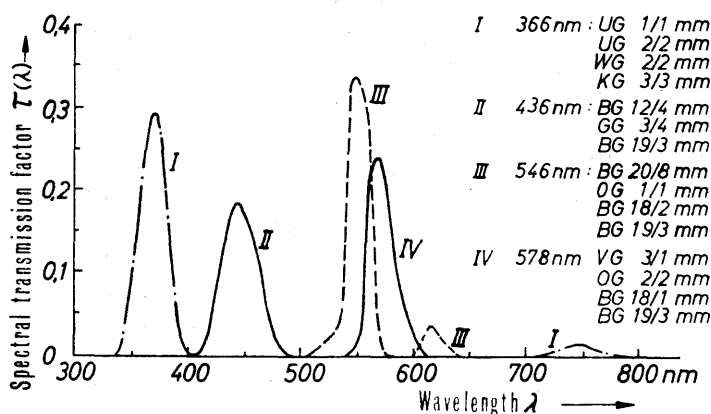


Fig. 40 Spectral transmission of monochromatic filters, Schott glasses.

On the other hand, an interference filter of narrow transmission range in conjunction with a line radiator does not produce a larger flux. But a superimposed continuous spectrum, of course, will then be largely eliminated by the interference filter.<sup>54,68,161</sup>

When an interference filter is used with one of the usual continuous radiators, e.g. a tungsten lamp, it is true that the spectral band isolated is narrow, but the radiation flux is often considerably smaller than if a suitable line radiator is selected. Sufficiently high monochromatic radiation flux is only obtained when a continuous radiator of very high intensity, e.g. a xenon high-pressure lamp, is used.

Monochromatic filters need (in conjunction with spectral lines) a larger number of radiators (e.g. the so-called spectral lamps) in order to isolate the desired lines. But when a continuous radiator is used in conjunction with interference filters, a single radiator will be sufficient. Another advantage is that interference filters within a certain wavelength band are available for any desired wavelength, while there is no choice in respect of spectral lines. Such

an arrangement for spectral measurements is also called a "filter monochromator."<sup>53,145</sup> These instruments can be successfully applied in all cases where one is content with a given selection of wavelengths. Of course, the expense will become considerable when one wants to use a filter monochromator for very many wavelengths.

It is, however, easy to avoid this drawback by using a so-called graduated interference filter. This can be described as a sequence of very narrow adjacent interference filters, with a practically continuous transition between the composing parts. Each point of the filter has therefore a selective transmission for its own wavelength; only a very small portion of the graduated filter is used at one time with the resulting drawbacks of limited transmission factor and poor spectral resolution of the radiation.

It should also be mentioned that interference filters must be used only with a small aperture in an approximately parallel bundle of rays, so that the effective optical paths are approximately the same for all rays.

When filters are used, one should always remember that the filter will become heated by the absorption process. This can be most inappropriate when the transmission of the filter depends on its temperature. Excessive heat may even destroy the filter, e.g. when it consists of several cemented glasses and the Canada balsam melts, causing streaks and other blemishes. The best solution is to use an additional filter so arranged in the optical system that the filter does not become over-heated. This could be an expendable filter with a wider transmission band.

For the elimination of the powerful infra-red radiation, special heat filters or liquid filters are used (e.g. Schott BG or KG with an optical path of a few millimetres; or water or copper sulphate solution of a few centimetres thickness).

One should always be careful with filters that they do not show somewhere in the spectral range a minute but nevertheless not negligible residual transmission. This becomes important when the detector possesses a superior sensitivity in this part of the spectrum, or when the radiator has a considerably larger emission at that point than in the specified transmission region of the filter. In this case too, pre-filtering of the radiation is a wise precaution.

Another point is that fluorescence can occur with some filters. If the fluorescent radiation is objectionable, it will be necessary to suppress the short-wavelength radiation which is responsible for the excitation, or to suppress the fluorescent radiation itself. Once more, this can be attained with a suitable additional filter.

*Manufacturers: Chance; Corning; Kodak (Wratten gelatin); Schott; interference filters, Balzers; Barr and Stroud.*

## VI. RADIATOR AND SPECTRAL APPARATUS

### 1. Introduction

Filters change slightly the angular distribution of the radiation by refraction, in the mostly plane-parallel filter layers. Generally speaking it is however not necessary to pay attention to these changes. If the filters are large enough, one can, without special preventive measures, alter the wavelength distribution of the radiation by inserting the filters at the most suitable position.

*In the case of the spectral apparatus described, it is on the contrary nearly always necessary to change the optical path by means of a suitable image formation in such a way that the highest possible radiation flux can pass through the instrument,<sup>116,128</sup>*

The cone of effective rays is limited by the entrance slit and the corresponding aperture of the collimating lens or mirror. When the radiation occupies a larger solid angle, the additional portion will only act as scatter radiation, which can be most objectionable. On the other hand, by restricting the cone so that the maximum effective solid angle is not reached, the instrument is not working at capacity.

This problem is further complicated by the following considerations:

- (a) nearly all the usual radiators are restricted in respect of emission area;
- (b) very often, the emission distribution is not uniform over the radiant surface, with regard to both the value of the intensity and its spectral distribution;
- (c) especially in the case of radiators with a very small radiant surface, such as arc and high-pressure lamps, the position of the radiant surface often shifts spontaneously, without any possibility of control.

How to resolve this problem depends on the experimental conditions.

### 2. Radiator not imaged on entrance slit

When the radiator has a large enough radiant surface and the radiant intensity  $L$  is uniform everywhere, it is not necessary to form an image of the slit. Naturally, a certain amount of scatter radiation will always be present.

The required minimum radiator area and the value of the pencil of rays producing scatter radiation can be calculated from Fig. 41 for a given distance. The main requirement is that the pencil of rays emitted by each point of the entrance slit fully fills the aperture. The shorter the distance between radiator and entrance slit, the smaller will be the minimum radiant area necessary to fill the aperture with radiation. But in practice there are limits to this minimum distance, so that a relatively large radiant area will always be necessary.

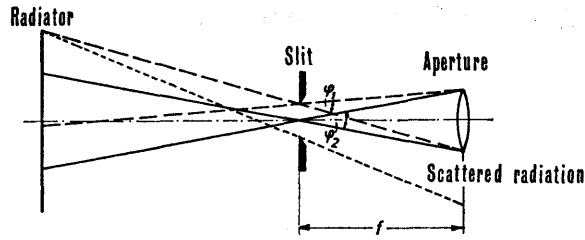


Fig. 41 Radiator not imaged on entrance slit.  $f$  = focal length of collimating lens or mirror;  $\varphi$  = aperture angle;  $\varphi_1 \approx \varphi_2$ .

The flux admitted by the instrument is:

$$\Phi = LbhO/f^2 \quad (34)$$

where  $b$  = width of slit;

$h$  = length of slit;

$O$  = area of the aperture;

$f$  = focal length of collimating lens or mirror.

When the radiant intensity per unit area  $L$  is not constant over the entire radiant area, we should remember that different surface elements with different aperture angles are included, and that the radiation emanating from them passes through the spectral apparatus at different places. As the absorption and reflection losses are not exactly the same at different points of a lens, mirror or prism, the radiation of different surface elements of the radiator will be weakened to different degrees on its passage through the instrument.

It is true that the slit is uniformly illuminated by the radiator, but the surface elements at the boundaries of the effective radiant area contribute to a lower degree to the total of the effective radiation in the instrument.

When the radiant surface is smaller than the required minimum, and one still works without image formation on the entrance slit, the available aperture is only partly used and the flux passing through the instrument is correspondingly smaller.

### 3. Radiator imaged on entrance slit

#### (a) Image formation without field lens

When an image of the radiant surface is formed on the entrance slit, the full aperture of the instrument will be used with a much smaller radiant area than without imaging, provided the image is produced in the correct way. This implies a sufficiently large relative aperture of the imaging lens, which should be at least the same as that of the instrument and a corresponding choice of distance and focal length. It is, however, unavoidable, even in the case of

the best arrangement, that a certain portion of the incident pencil of rays does not reach the aperture, and acts as a possible source of scattered radiation (see Fig. 42).

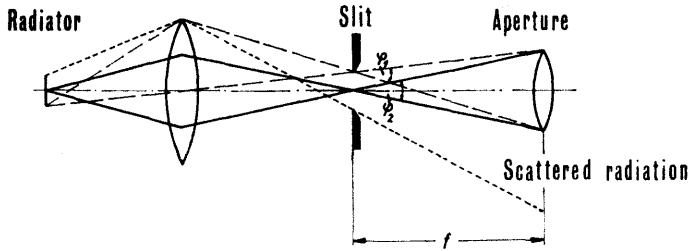


Fig. 42 Radiant area imaged on entrance slit; without field lens.  $f$  = focal length of collimating lens or mirror;  $\rho$  = aperture angle;  $\rho_1 \approx \rho_2$ .

The flux passing through the instrument is the same as before when the losses caused by the optical system are disregarded:

$$\Phi = LbhO/f^2 \quad (34)$$

(b) Image formation with field lens

All scattered radiation can be avoided by arranging an additional lens as "field lens" immediately in front of the slit. This lens forms an image of the collimating lens or mirror on the aperture. The collimating lens or mirror can then be smaller and, when the optimum arrangement is attained, all radiation present in the slit will reach the aperture and none will pass outside, possibly to be scattered (see Fig. 43).

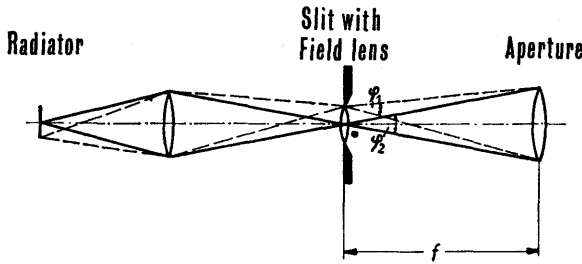


Fig. 43. Radiant area imaged on entrance slit; with field lens.  $f$  = focal length of collimator lens or mirror;  $\phi$  = aperture angle;  $\phi_1 \approx \phi_2$ .

Disregarding losses, the flux is expressed as before by:

$$\Phi = LbhO/f^2 \quad (34)$$

In both cases *a* and *b*, the distribution of the radiant intensity per unit area on the surface of the radiator will be reproduced in the image formed in the entrance slit. The slit will therefore not be irradiated uniformly when the radiant surface itself is not completely uniform.



#### 4. Radiators not imaged on entrance slit, but with field lens

In many cases the above lack of uniformity (according to 3a or 3b) is objectionable. We should also take into consideration that the non-uniformity after passing through the instrument is the same at the exit slit, because the image of the entrance slit is formed there.

In order to obtain uniform irradiation of the slit, one can operate without image formation and reduce at the same time the required minimum size of the radiant surface by using a field lens in front of the slit. No other lens is used. In this case the field lens images the radiant surface on the aperture (see Fig. 44).

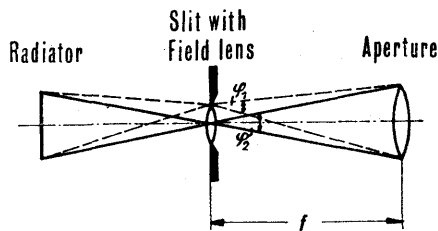


Fig. 44 Radiator not imaged on the entrance slit; with field lens.  $f$  = focal length of field lens;  $\varphi$  = aperture angle;  $\varphi_1 \approx \varphi_2$ .

Disregarding losses, the radiation flux is:

$$\Phi = LbhO/f^2 \quad (34)$$

Under these conditions the distribution of radiant intensity per unit area in the radiant surface will now appear at the aperture diaphragm. The result is that the radiation emitted by different points on the radiant surface will also pass through corresponding diverse parts of the collimating or camera lens and of the prism. This may render more perceptible the variations in absorption and reflection losses.

#### 5. Image formation by a lens-raster

When the radiant surface is very small and changes its position spontaneously the image of the radiator can be formed (using methods 3a or 3b) at times partly or entirely outside the slit. Strong fluctuations of the transmitted radiation flux will occur, resulting in a very variable response throughout the instrument.

This can be remedied by using a so-called lens-raster.<sup>138</sup> Such a system consists of a great number of minute identical lenses (or mirrors), arranged in a single plane. Instead of a single image of the radiator, many images are produced, all lying closely together.

If the number of lenses or mirrors is large enough in relation to the slit dimensions, any change in the radiant surface position will result in some of the images moving from the slit. On the other hand, adjacent images will take their place. In this way large fluctuations in the radiation flux can be avoided. The difficulty here is to determine the correct relationship between the fineness of the raster system, the focal length and the relative aperture.

## 6. Conclusions

There are no basic differences between the above methods whether one is using lenses or concave mirrors. The drawback of using lenses lies in the fact that chromatic aberration can alter the radiation distribution of the radiation passing through the instrument.

It is, however, not possible in practice to replace a field lens by a concave mirror, so that use of a field lens must be cut out when chromatic aberration or poor transmission of the lens material makes necessary the use of mirrors.

It can be deduced from equation (34) that by suitable arrangements all methods will yield the same value for the flux, because, in effect, there is produced at the slit a radiation source of the same radiance. If the slit always has the same area then the total flux through it is constant.

In the monochromator, the entrance slit is imaged on the exit slit. The above is therefore also valid in this case, but only for any given wavelength, because of the spectral dispersion. Disregarding any radiation losses, the spectral radiant intensity per unit area in the exit slit, in the entrance slit and in the radiator, are all the same under the conditions stated. The total radiant intensity in the exit slit is then determined by the contributing wavelength interval, while one can take any radiation losses into account by corresponding transmission factors.

*The exit slit can therefore be considered both as a receiver with a certain irradiance, and as a radiator with a certain radiance or radiant intensity per unit area.*

## VII. INTRODUCTION TO RADIATION DETECTORS

### 1. Principles

A radiation detector is defined as an instrument which indicates in any fashion the action of electromagnetic radiation of a specified wavelength range.

When no adequate data are available for the ratio of value of the indication to the energy of the radiation, the indications are essentially qualitative. Nevertheless such a detector can be usefully applied to prove the absence of radiation, or when the sensitivity remains sufficiently constant (during short periods of time), it is also possible to determine equality or otherwise of different radiations.

If a detector is to be used for measurement, one must know the ratio of the indication to the radiation energy. A further requirement will usually be that the values are proportional one to the other. In individual cases, one should always check for which range these conditions are met.<sup>77,191</sup>

Apart from the value of the radiation energy, the detector indication usually also depends on the wavelength of the radiation. Such a detector giving different indications for the same energy in different wavelength ranges is described as "selective."

Conversely, a detector, the indication by which does not depend on wavelength but only on energy is called "non-selective." It will be obvious that the latter type of detector is very important for many measuring purposes. In analogy with reflection terminology, it is sometimes called a "black detector." This name is derived from the fact that for thermal detectors non-selectivity is obtained by a grey or black absorption layer.

### 2. Sensitivity

The quotient of the indication  $I$  by the detector and the radiant incident energy  $Q$  is the sensitivity  $s$  of the receiver.<sup>8</sup> If this is constant as a result of a proportional relationship between indication and radiation:

$$s = I/Q$$

or

$$Q = I/s \quad (35)$$

The characteristic value of the field of radiation at the position of the detector is the irradiation intensity  $E$ . When the effective area  $f_2$  of the detector is known, the corresponding radiant flux  $\Phi$  received by the detector can be calculated.

The indications of the detector can be expressed in any desired way, e.g. on a graduated scale. It is, however, usual to express the indication in an electric value, such as current  $i$  or voltage  $u$ .

According to the values used, the following expressions can be obtained for the sensitivity:

$$\begin{aligned}
 s_i^* &= \frac{i}{\Phi} \left( \text{e.g. in } \frac{\text{amp}}{\text{watt}} \right) \\
 s_i &= \frac{i}{E} \left( \text{e.g. in } \frac{\text{amp}}{\text{watt/cm}^2} \right); \quad s_i = s_i^* \cdot f_2 \\
 s_u &= \frac{u}{\Phi} \left( \text{e.g. in } \frac{\text{volt}}{\text{watt}} \right); \\
 s_u &= \frac{u}{E} \left( \text{e.g. in } \frac{\text{volt}}{\text{watt/cm}^2} \right); \quad s_u = s_u^* \cdot f_2
 \end{aligned} \tag{36}$$

### 3. Spectral sensitivity

The dependence of sensitivity upon wavelength has not been taken into account in the definitions given so far. To deal with this problem we must select a narrow band of the spectrum, measure the required quantities and attribute these values to monochromatic radiation of the mean wavelength of the load used.<sup>8</sup> The spectral sensitivity, indicated as a function of wavelength and the measured values by the subscript  $\lambda$ , is then:

$$\begin{aligned}
 s_i^*(\lambda) &= i_\lambda / \Phi_\lambda & s_u^*(\lambda) &= u_\lambda / \Phi_\lambda \\
 s_i(\lambda) &= i_\lambda / E_\lambda & s_u(\lambda) &= u_\lambda / E_\lambda
 \end{aligned} \tag{37}$$

and in general

$$s(\lambda) = l_\lambda / Q_\lambda \quad \text{and hence} \quad Q_\lambda = l_\lambda / s(\lambda)$$

The dimensions of spectral sensitivity and sensitivity are the same.

The above equations arise because, if  $\Delta\lambda$  is the width of the band of wavelengths used for the measurements, the current actually measured is  $i_\lambda \Delta\lambda$  and the flux  $\Phi_\lambda \Delta\lambda$ . When the sensitivity is calculated as the ratio,  $\Delta\lambda$  disappears. It is necessary to specify that  $\Delta\lambda$  must be small in order to estimate  $\lambda$  accurately.

Often we only want to know the relative spectral sensitivity. This can be calculated by dividing by the value at an arbitrarily selected reference wavelength  $\lambda_0$ :

$$s(\lambda)_r = s(\lambda) / s(\lambda_0)$$

so that

$$s(\lambda) = s(\lambda_0) s(\lambda)_r = C s(\lambda)_r \tag{37a}$$

where  $C = s(\lambda_0)$  constant not dependent of wavelength.

The maximum value of the spectral sensitivity is usually used as a reference. The relative spectral sensitivity is a dimensionless number. For the reference wavelength  $\lambda_0$  this number equals 1 according to definition. In the case of

non-selective detectors, this number is a constant (also = 1) while with selective detectors it depends on the wavelength.

#### 4. Overall sensitivity

Assuming a known spectral sensitivity  $s(\lambda)$ , we obtain for the larger wavelength interval ( $\lambda_1$  to  $\lambda_2$ ), by calculation of the sensitivity indication  $I$  and irradiation intensity  $E$  the corresponding sensitivity:

$$s(\lambda_1, \lambda_2) = I/E = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda = \int_{\lambda_1}^{\lambda_2} E_\lambda s(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda \quad (38)$$

hence

$$E = I/s(\lambda_1, \lambda_2)$$

Value  $s(\lambda_1, \lambda_2)$  can be termed the overall sensitivity in the spectral range concerned. It depends on the spectral radiation distribution  $E_\lambda$  used.

There are some special cases:

(a) Relative spectral radiation distribution  $(E_\lambda)_r$  is known. As  $E_\lambda = E_\lambda(\lambda_0)(E_\lambda)_r$ , the integrals can be calculated:

$$s(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r s(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r d\lambda \quad (38a)$$

(b) Equal-energy spectrum  $E_\lambda = \text{constant}$ :

$$s(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} s(\lambda) d\lambda / (\lambda_2 - \lambda_1) \quad (38b)$$

The overall sensitivity equals the average of the spectral sensitivity in the wavelength ranges  $\lambda_1$  to  $\lambda_2$ .

(c) Non-selective detector  $s(\lambda) = \text{constant} = s$

$$s(\lambda_1, \lambda_2) = s \quad (38c)$$

The overall sensitivity equals the constant spectral sensitivity. The term "sensitivity" by itself is also often used.

#### 5. Arrangement of the detector

We are now concerned with the best possible position of the detector. A primary consideration is the size of the radiation area and the corresponding solid angle, as well as the size of the detector.

As all detectors give normally an increased indication (with a constant irradiation intensity) when the detector area is increased, a large detector is desirable, provided a satisfactory radiation field is available. The same effect can also be obtained with a small detector area when the radiant surface is imaged on the detector.

When both radiant surface and detector surface are at right angles to the direction of radiation, we find for the radiation intensity  $E$  at the receiver (according to II, 2, equation (9b):

*Without image formation*

$$E = I/r^2 = Lf_1/r^2 \quad (9b)$$

where  $f_1$  = area of radiant surface;  
 $r$  = distance between detector and radiator.

*With image formation (disregarding losses)*

$$E = Lf_s/r^{*2} \quad (9c)$$

where  $f_s$  = area of aperture of lens or concave mirror;  
 $r^*$  = distance between lens or mirror and detector.

*The lens or concave mirror acts therefore as a radiator of the same radiance, when losses are disregarded.*

#### *Derivation*

When  $d$  = distance between radiator and mirror or lens;  $f_1$  = area of radiant surface and  $f_2$  = area of detector surface, we find:

$$\Phi = Lf_1 \cdot f_s/d^2 \quad f_2/f_1 = r^{*2}/d^2$$

therefore:  $\Phi = Lf_2 f_s/r^{*2}$

and:  $E = \Phi/f_2 = Lf_s/r^{*2}$

There are however cases when the spectral distortions caused in the process of image formation, for example by absorption and reflection, are objectionable, particularly in the measurement of total radiation. Furthermore, an increase in area of the detector is very often limited by the design of the instrument, or any variation can only be between very narrow limits.

As a rule we can say that if the type of detector concerned is available with a surface of sufficient area, no image formation is necessary. In all other cases, image formation will bring improvement, although there may be other reasons against its use.

We should also mention that in the case of polarized radiation, the placing of the detector surface in relation to the plane of polarization can influence the sensitivity of the detector. This is particularly the case for photoelectric detectors. Sensitivity often depends also on the direction of the incident radiation.

## 6. *Measurement with continuous radiation and intermittent radiation*

So far we have not mentioned the time factor in relation to radiation. In normal cases, a detector, which has not received any previous radiation, is exposed to a constant radiation, which is shut off after a certain period. This is called continuous irradiation.

The perfection of alternating current measuring techniques, in particular those concerning the amplification of very weak signals, has led to the application of the same techniques to radiation detectors. This can be achieved with periodically interrupted (chopped) or, better, sinusoidally modulated radiation. The latter is desirable, but not absolutely necessary.<sup>94,112,120,121,122</sup>

The output of the detector is then equally modulated and can be measured by A.C. preferably with a narrow band circuit of matching frequency.

A prerequisite, of course, is that the detector must be capable of following the sequence of radiation pulses. It should therefore possess a sufficiently short response time, usually characterized by the time constant as it is called, namely the time needed by the detector to register the fraction  $1 - e^{-1} = 0.63$  of the maximum output, when subjected to constant irradiation. One may meet difficulties in this connection, particularly when using thermal detectors.

The advantages of this method are:

- (a) ease of amplification of the detector impulses;
- (b) elimination of all faults not inherent in the modulation or amplification of the frequency used.<sup>27</sup>

The following may be regarded as drawbacks:

- (a) the theoretical limit of sensitivity can sometimes be higher using continuous light;
- (b) when the detector is to be used as a measuring device of fixed sensitivity, the stability of the system will be important.

For exact measurements, especially at very weak radiation levels, as well as in the case of thermal detectors, one should not use the modulation technique. For measurements of less exactitude and in cases where the detector is only used as a balance indicator, the intermittent or chopped radiation method is to be recommended. This is particularly the case when control apparatus is connected.



## VIII. THERMAL RADIATION DETECTORS

### 1. Principles

Only thermal radiation detectors can be made to be satisfactorily non-selective. They use the heat engendered by irradiation to create the highest possible change in temperature in the detector. A change in some other value (e.g. in pressure, thermo-e.m.f., capacity, length, volume, etc.) which is caused by the change in temperature, is then measured. In principle, any property which changes with temperature, can be used.

The proportionality between input of radiation energy and indication required when the detector is used for measurements, is met in full, provided that the incident radiation flux and the accompanying temperature changes are not too great. When large differences in temperature occur, deviations from linearity will result. Measurement of large radiation flux is often inconvenient for this reason, especially as the commercially available detectors are made as sensitive as possible. Most thermal radiation detectors operate in "thermal balance," i.e. the increase of temperature causes a dissipation of heat which balances the incident radiation flux. If the latter is high, then a high temperature of the detector is necessary to dissipate the heat, and therefore the indication of the detector is high.

In order to arrive at large changes in temperature in short irradiation periods (small time constant), the first consideration in the design of all thermal detectors is to make the thermal capacity as small as possible. Dissipation should also be small, but not too small; for dissipation, in conjunction with thermal capacity, is decisive for the time constant:

$$t = K/V \quad (39)$$

where  $t$  = time constant;

$K$  = thermal capacity;

$V$  = heat loss per second per degree.

*Thermal capacity should be as small as possible, heat dissipation (allowing for thermal capacity) sufficiently large to bring the time constant to the desired value.*

As these two properties are often difficult to change separately, there are certain restrictions.

The best solution is for the radiation receiving element of the detector to be flat and of narrow strips or thin foil.

Uniform absorption of different wavelength ranges is obtained by a black layer over the irradiated side of the detector. Suitable blackening substances

are various kinds of soot, metal oxides, or metals in an amorphous state. The latter can be produced electrolytically or by evaporating of metals in suitable gases at reduced pressure.

Layers made in this manner show a very high degree of absorption in wide bands of wavelength, practically independent of the wavelength. When extremely accurate measurements are envisaged, it should still be checked to what degree these layers have non-selective absorption.

To reduce heat dissipation in the ambient atmosphere (considering transmission or convection with thin strips or foils) thermal detectors are preferably placed in a high vacuum, where only the radiation losses are of importance. It is obvious that in this case a high-quality plane-parallel window made of suitably transparent material must be used.

There are no window materials known that are equally well suited for the entire optical wavelength range. This means that the most suitable material should be selected for each band. Another consideration is that the window should not produce unwanted selectivities of the detector through reflection and absorption in the transmission range.

Detectors mounted in vacuum always have a higher sensitivity than those in air. The ratio of 5–10 is normal. The gain is therefore considerable. Apart from the higher sensitivity, vacuum detectors have the advantage of being much less prone to disturbance. With a free-air thermal detector not only air movements caused by objects moving in the neighbourhood result in disturbances, but especially so do adiabatic compressions which are unavoidable in windy weather, even in closed rooms.

A zero shift, caused by changing temperature conditions in the room and in the instrument, cannot be entirely eliminated when operating with continuous radiation. This shift can be considerably reduced, but hardly ever eliminated, by suitable compensation.

Compensation arrangements usually employ a detector of exactly the same design as the main detector, but the second detector does not receive any irradiation. When the two detectors are close together, both are affected by all other external conditions, including temperature, and the differential response will be a measurement of the incident radiation only.

## *2. Thermoelectric radiation detector*

The thermoelectric detector has a special place amongst thermal radiation detectors, because here the heat is directly transformed into electrical energy. Use is made of the thermoelectric current which is produced by irradiation and consequent heating of one thermo-junction of a thermo-couple. The current can be measured directly, while the cold thermo-junction remains at room temperature. When irradiation of the cold thermo-junction cannot be avoided, the junction is brought into contact with a good heat conductor of high heat capacity.

Provided the radiation intensity is not too high, the temperature increase of the cold junction will be very small.<sup>33,55,67,99,165,172</sup>

When a single thermo-couple with an irradiated thermo-junction is used, it is called a radiation thermo-couple (see Fig. 45).

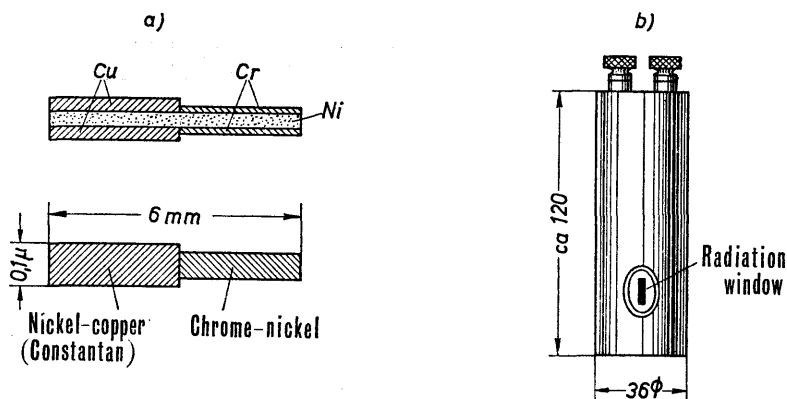


Fig. 45 Radiation thermo-couple (C. Müller). (a) thermo-strip. A nickel strip is coated partly with copper and partly with chrome. Diffusion produces nickel-copper (constantan) and chrome-nickel. (b) the complete instrument. Unspecified measurements are in millimetres.

When a number of thermo-couples are mounted in series in such a way that the thermo-junctions to be heated lie in the plane of irradiation, it is possible to use a larger portion of the radiation field. This kind of instrument is called a thermopile (see Figs. 46 and 47).

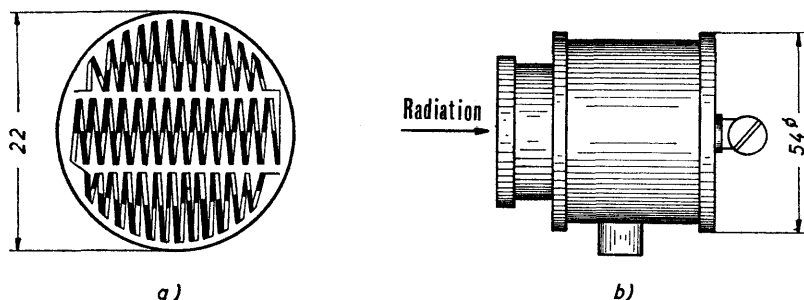


Fig. 46 Large-surface thermopile; after Moll (Kip en Zonen). (a) detector surface: the thermo-strips are arranged in zigzag fashion, while the ends are attached to solid, individually insulated metal pins (not shown); (b) the complete instrument. Measurements in millimetres.

The cold thermo-junctions are protected against irradiation as much as possible. The transfer of heat from hot thermo-junctions should be small. On the other hand, in order to avoid zero shift, it is essential that when no irradiation takes place, no changes in temperature occur between cold and hot

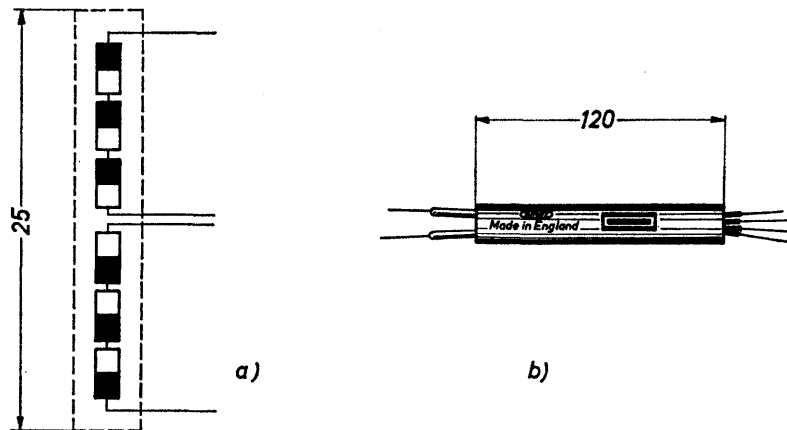


Fig. 47 Linear thermopile; after Schwartz (Hilger and Watts). (a) detector surface; (b) the complete instrument. Measurements in millimetres.

thermal-junctions, even when there are fluctuations in the ambient temperature. This means that cold and hot thermo-junctions must be close together.

The individual elements of a thermopile can take the form of thin strips arranged in the field of irradiation. Often, individual small receiving discs

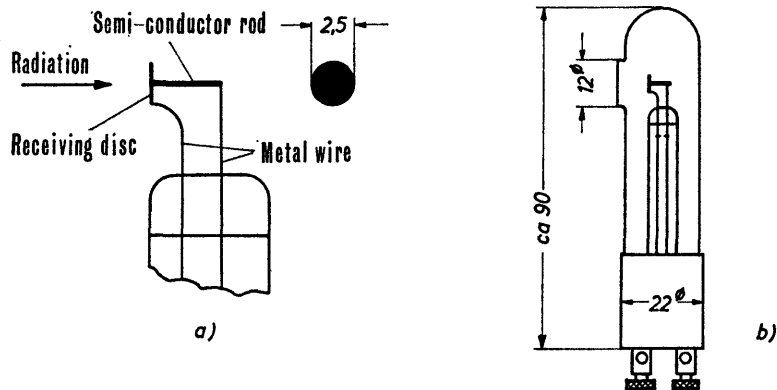


Fig. 48 Radiation thermo-couple (Pyro-Werk). (a) detector (schematic); (b) the complete instrument. Measurement in millimetres.

are exposed to radiation and these discs carry the hot thermo-junction on their reverse side (see Fig. 48). Thermoelectric materials are suitable combinations of two dissimilar metals, although in recent times semi-conductors have been used for this purpose.

To obtain a greater concentration, a small mirror is sometimes included in the design. There are two ways of doing this:

By placing the concave mirror behind the receiver, an incident parallel pencil of rays is concentrated on the receiver. Both spherical and cylindrical mirrors are used; the latter when a line image is required of the slit of a spectral instrument. This increases the irradiation intensity (see Fig. 49a).

In another design, a spherical mirror is placed between the source of radiation and the receiver, so that the radiation reaches the receiver through a central hole in the mirror. The receiver itself is positioned at the centre of curvature of the mirror. This arrangement ensures that any radiation that might be reflected by the receiver is re-directed to the receiver. The role of the mirror, therefore, is to increase the degree of absorption (see Fig. 49b).

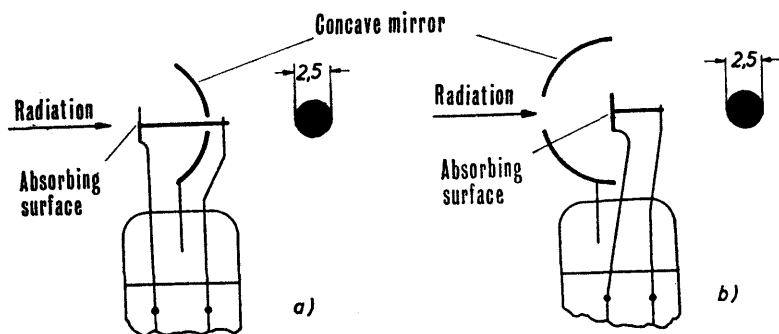


Fig. 49 Radiation thermo-couples with incorporated concave mirror; after Hase (Pyro-Werk). (a) mirror for radiation concentration; (b) mirror for 'black body' measurements. Measurements in millimetres.

Whether a thermal detector with a small receiving disc, a so-called linear thermo-couple with a narrow rectangle for the receiving surface, or a thermopile with a larger receiving surface is preferred, is a question of size and shape of the available irradiated areas.

The compensation principle (comparison with a similar non-irradiated receiver) is also applied to thermo-couples. The comparison instrument may be connected with the circuit of the measuring instrument either in parallel or in series. The choice of circuit depends on the measuring equipment (see Fig. 50).

*Manufacturers: Phys. Techn. Werkstätten (Prof. Heimann); Pyro-Werk; Eppley Laboratory Inc.; Hilger and Watts; Kip en Zonen.*

Measuring apparatus for use in conjunction with thermoelectrical radiation receivers can employ all usual methods for measuring small voltages. In the majority of cases it will be necessary to choose highly sensitive instruments because the effects to be measured are very small. Galvanometers of high sensitivity are usually employed. The best method to avoid deviation from the assumed linear relationship between thermal voltage and radiation value is

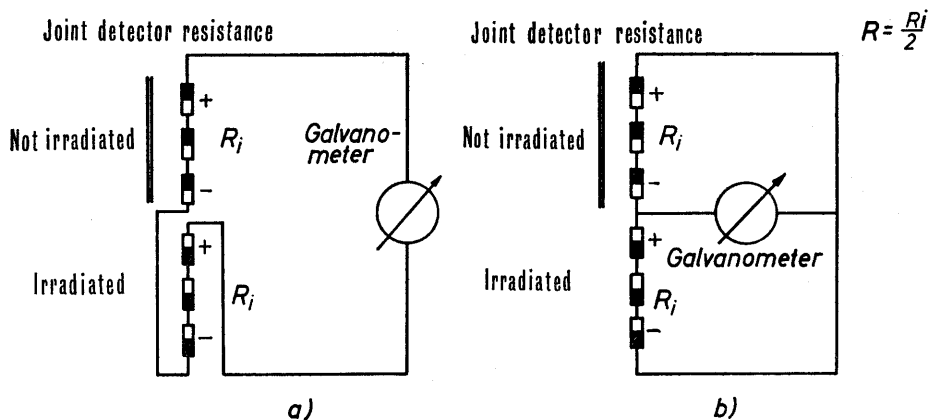


Fig. 50 Linear thermopile after Schwartz (Hilger and Watts) in compensating circuit. (a) in series; (b) in parallel.

to measure the thermal voltage with a device taking no energy. In this case, no account has to be taken of the calibration of the measuring instrument, because it only serves as zero indicator. High-sensitivity photoelectric compensators are particularly useful for recording purposes. In these the light beam

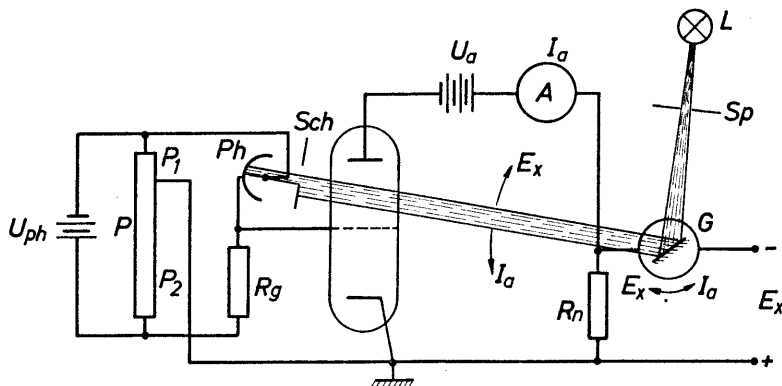


Fig. 51 Photoelectric compensator (W. Hübner).

- |                             |  |
|-----------------------------|--|
| $A$ = recording instrument, | $E_x$ = potential to be measured,        |
| $G$ = galvanometer,         | $I_a$ = anode current,                   |
| $L$ = light source,         | $P_1, P_2, P_3$ = potentiometers,        |
| $Ph$ = photoelectric cell,  | $R_g, R_n$ = resistors,                  |
| $Sch$ = screen,             | $Sp$ = slit,                             |
| $U_a$ = anode potential,    | $U_{ph}$ = photoelectric cell potential. |

The potential to be measured  $E_x$  is connected to the galvanometer  $G$ , whose light beam regulates a current  $I_a$  through a photoelectric cell  $Ph$  in such a way that the potential drop at  $R_n$  equals  $E_x$ ; current  $I_a$  is therefore proportional  $E_x$ .

of a galvanometer regulates the compensation voltage by illuminating a photo-electric cell more or less according to the deflection of the galvanometer<sup>78,104</sup> (see Fig. 51).

Nowadays, the microradiometer of C. V. Boys, though famous in the history of science is hardly ever used as a thermoelectric detector. It is a combination of thermo-couple and galvanometer. The coil of the galvanometer consists of a single winding, which forms the thermo-couple, whose hot thermo-junction is irradiated. A certain advantage lies in the fact that detector and measuring

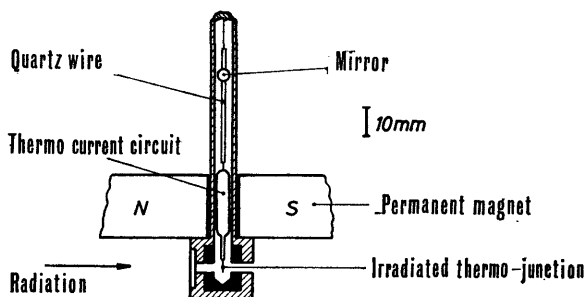


Fig. 52 Microradiometer.

apparatus are combined in one physical unit, but it is prone to disturbance and also the indication time is rather long, while the sensitivity is no greater than with modern thermal radiation detectors (see Fig. 52).

### 3. Bolometer

With thermoelectric detectors, heating of the detector causes direct changes in the potential or current, which can be measured. With the bolometer, however, one measures the changes in an electrical resistor (or a capacity). As the energy required for the measurement is supplied by external sources, the main task of the bolometer is to control the measurement. But the energy fed to the measuring element cannot be increased indefinitely since this causes an additional heating of the bolometer (Joule effect). With bolometers too, compensation is applied by comparison with a similar non-irradiated detector. This is even more necessary than for thermo-couples, because the heating caused by the energy supplied by the external source can produce an additional zero flutter in cases where the latter is not absolutely constant.<sup>25,26,35,38,67,84,97,131,143,172</sup>

#### (a) Resistance bolometer

The oldest and still most widely used form of bolometer is the resistance bolometer where a fine wire or strip is exposed to radiation and its changes



in resistance are measured. For this purpose one automatically chooses the Wheatstone bridge. The bolometer forms one arm of the bridge with a similar (compensating) unit in the series or parallel area, while the other resistances are of a type independent of the temperature.

A linear bolometer has only a single narrow strip. A large-surface bolometer has a strip extending zigzag-fashion, similar to that in a thermopile.

The sensitivity can be doubled by using detectors in two diagonally opposite bridge arms. In this case for correct compensation all arms must be identical.

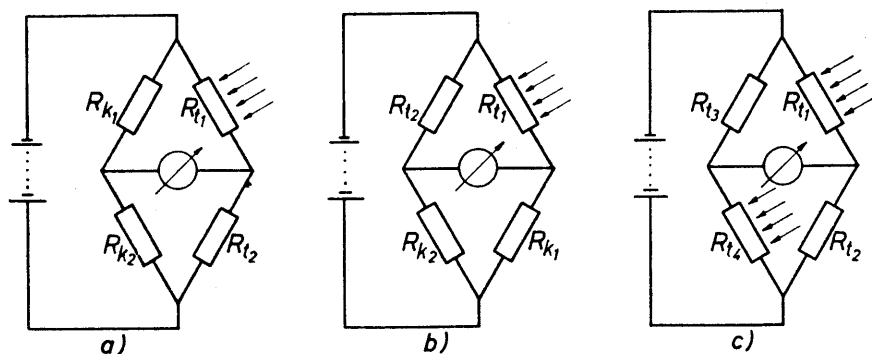


Fig. 53 Bolometer. (a) detector metal (positive resistance-temperature coefficient); (b) detector semi-conductor (negative resistance-temperature coefficient); (c) irradiation of two arms of Wheatstone bridge.

$R_t$  = detector resistance depending on temperature

$R_k$  = comparison resistance not dependent on temperature. Usually all resistors are of the same value.

As even the manufacture of two identical detector elements is very difficult, the use of a total of four to increase sensitivity is rare.

The resultant action between the Joule effect, which is present even when no irradiation takes place and the applied radiation flux, enables special circuits depending on the sign of the resistance-temperature coefficient to be provided. This must be borne in mind when semi-conductors with a negative resistance-temperature coefficient are used. Consideration of possible burning out of the detector (see Fig. 53) must not be overlooked.

*Manufacturers: Phys. Techn. Werkstätten (Prof. Heimann); Vacumed, Lassenwerk; Carl Zeiss, Oberkochen.*

We should mention that it is sometimes recommended that the value of the resistor in series with the detector be as large as possible. It is true that this increases the sensitivity by a factor up to 2, with the same detector load, but with the high series resistance required, potential differences of such a high value are needed that this method is used only very rarely.

A perfect balance is practically impossible with a bolometer, due to the fact that two detector resistors manufactured under identical conditions, will always show slightly different resistance values. As a result, all fluctuations in the bridge potential from the auxiliary supplies will produce fluctuations of the zero. Finally, disturbances caused by changes in the ambient temperature—as already mentioned in respect of thermopiles—constitute a further drawback.

These disturbances can be avoided in principle by using modulated radiation, which is therefore usual with bolometers. The required small time constant is obtained in this case by intentionally not reducing the heat dissipation too much. For this reason, very thin layers on massive supports are often used. This gives the additional advantage of being able to use materials of smaller mechanical strength, which it would be impossible to use as self-contained strips. This method is mainly employed for semi-conductors with large resistance-temperature coefficient (thermistors).

*Manufacturers: Barnes Eng. Comp.*

#### (b) Capacitance bolometer

In a capacitance bolometer, the detector consists of a thin insulating foil, e.g. mica, coated on both sides with a thin layer of metal. All other conditions correspond with those of the resistance bolometer.<sup>123,187</sup>

In practice, only modulated radiation is used, because measurement of a change of capacitance—as produced by the detector—is easier to measure by A.C. methods. The connection to an A.C. amplifier is more satisfactory than with the resistance bolometer with its usually small resistances. Nevertheless, the capacitance bolometer has not found much application.

### 4. Detectors using longitudinal or volume expansion

With the exception of the ancient differential thermometer of Leslie these two basically similar methods have only been used in recent times.

#### (a) Thermal detector after R. V. Jones

The receiver here is a thin metal strip, the length of which is changed as a result of thermal expansion caused by irradiation. This change in length is directly transferred to a tensioned strip (as used in a galvanometer), to one edge of which the receiver strip is attached, and causes a slight torsion which can be measured by means of a mirror fixed on the strip, a suitable lamp and scale being required for the display. The further possibilities of this remarkably simple and yet sensitive design appear to be endless<sup>87,88</sup> (see Fig. 54).

### (b) Pneumatic detectors

Once more, the receiver itself is a thin blackened foil placed in a small air-tight, gas-filled chamber. The heat absorbed by the foil is transmitted to the gas, the pressure of which therefore changes. This change in pressure can be measured in different ways.<sup>32,60,61,90</sup>

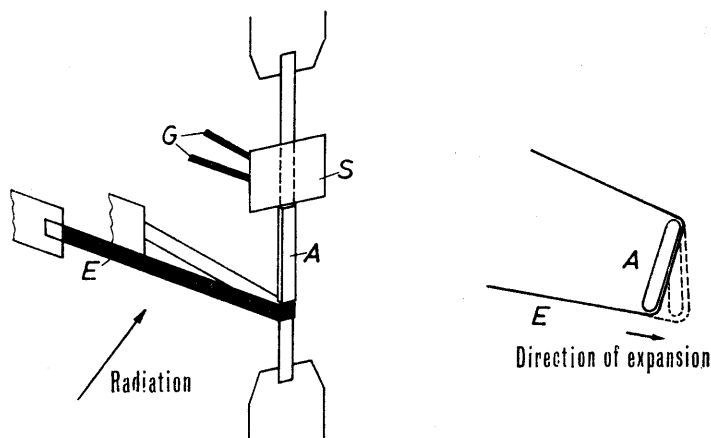


Fig. 54 Thermal detector (R. V. Jones). A = suspension band; G = counterweight; S = mirror; E = receiving strip (thickness:  $0.1 \mu$ ; width:  $0.25 \text{ mm}$ ).

In one design, part of the chamber wall is in the form of a thin metallized membrane, which in turn forms one of the two plates of a capacitor. The change in capacitance which is measured is produced by a deflection of the membrane as a result of change in pressure (see Fig. 55).

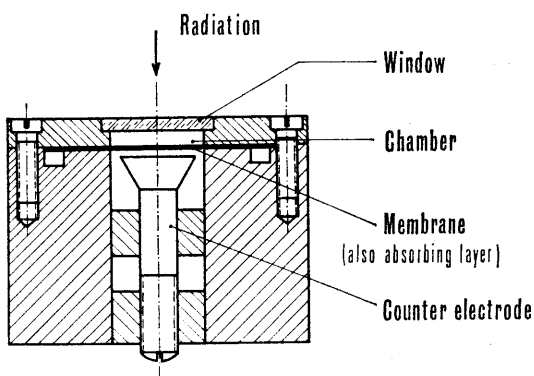


Fig. 55 Pneumatic detector (Böttcher). Measurement of the change in capacitance.

In another design, the membrane acts as a flexible mirror on which a convergent pencil of light rays is directed. A change in pressure causes a change in the curvature of the mirror and thereby the convergence of the reflected pencil of light. The incident convergent pencil initially passed through a grating and the reflected pencil is made to form an image of the grating on a second grating in such a way that no light passes through it and no current is generated in a photocell placed to receive light coming through the second grating. The slightest movement of the flexible mirror produces a relatively large current. This is a case of amplifying the reading of a thermal detector by means of a photoelectric detector (see Fig. 56).

This type of amplification is extraordinarily sensitive, although the reading is proportional to the radiation flux over only a limited range. The small time constant which can be attained with this type of detector is also remarkable; values of the order of milliseconds can be reached.

*Manufacturers: Eppley Laboratory Inc.; Unicam Instruments Ltd.*

## 5. Sensitivity limits

The sensitivity of a radiation detector is limited by statistical fluctuations. Neglecting the fluctuations caused by incident radiation, which are very small, fluctuations of heat energy  $E = kT/2$  occur per degree of freedom. These occur in thermal detectors in the following ways:

- (a) as spontaneous fluctuations in the detector temperature<sup>40</sup>;
- (b) as thermal agitation noises (Nyquist noise, Johnson noise) in the detector, when an electrical measurement method is used.<sup>132,189</sup>

Disturbances in auxiliary measuring instruments can usually be kept so small that they are negligible.

It will be obvious that the spontaneous temperature fluctuations set the real limits. The heat capacity  $K$  is the decisive factor:

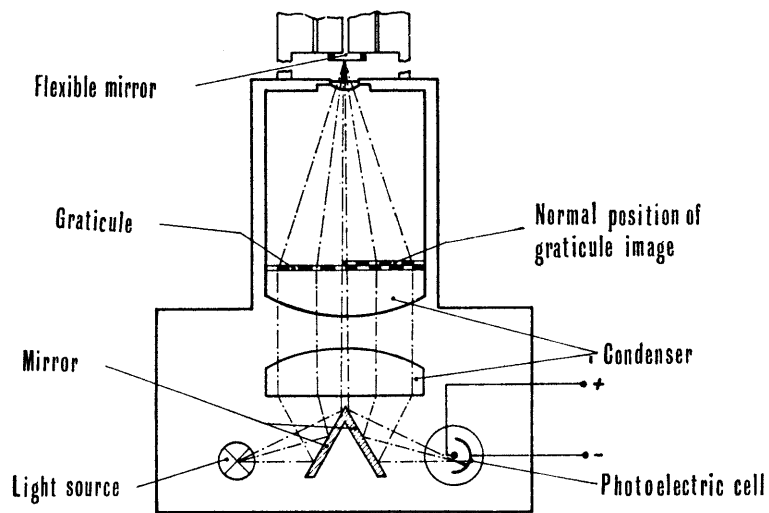
$$\Delta T = T\sqrt{k/K} \quad (40)$$

where  $T$  = absolute temperature;

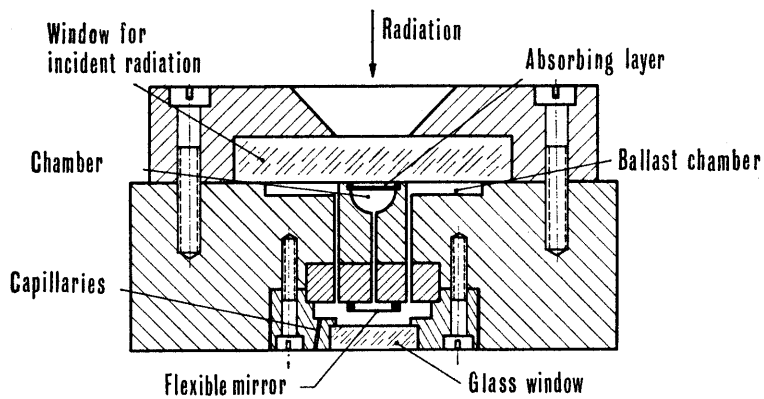
$\Delta T$  = mean temperature fluctuation;

$k$  = Boltzmann's constant.

The influence of disturbances caused by thermal agitation noises can only be estimated in conjunction with the corresponding electrical data, e.g. value of the thermo-e.m.f., the temperature coefficient of resistance, the electrical resistance, etc., as well as the circuits. In the light of recently established experimental values, the limit imposed by thermal noise is ten times higher than is the case for the thermodynamic limit determined by temperature fluctuations. Lowering the temperature of the detector will decrease the fluctuation of



a)



b)

Fig. 56 Pneumatic detector (Golay). Measurement by deflection of a pencil of light. (a) optical measurement device; (b) chamber.

heat energy and always improve the maximum sensitivity. As the temperature of the very thin detector layers is basically determined by the temperature of the surrounding housing, it is necessary to cool the latter. But because this is a rather complicated procedure, it is usually preferred to work at room temperature.

For the reasons stated above a set of readings under identical conditions would show variations. Even if the detector were perfect, in the sense that it would record every quantum received by it, a set of readings by it would show similar but smaller variations. The percentage accuracy in both cases increases with the total number of quanta measured. To reach the same percentage accuracy the perfect detector requires fewer quanta than a real detector. The efficiency of the real detector is therefore measured by the ratio of the corresponding number of quanta.

As the measurement limit is represented by an energy value and the measurement characteristic by a flux value, the period of measurement (or, in the case of modulated-light measurements, the effective band width of the amplifier in relation to the amplitude) will also be important. By making the period of measurement long (or the band width small), even in the case of a small radiation flux, the energy received by the detector will be great compared with the fluctuation in energy. Increasing the period of measurement or reducing the band width therefore improves the signal to noise ratio. On the other hand, we should take into consideration that we can take a greater number of readings during a given available period when the individual measurements only take a short time. The discrimination and limits of measurement will then be improved by taking an average of the readings. It may, in practice, be better to do this than merely increase the time of measurement. It should also be remembered that with increasing measurement time, the influence of external disturbances also increases.<sup>23,25,27,49,79,117,162</sup>

R. C. Jones studies the problems of radiation detectors in great detail. To estimate the "merit factor" of detectors he uses as the standard the thermodynamic limit of an ideal detector used at room temperature, which suffers heat losses only by radiation. With regard to the receiving surface and the reaction time or band width, the units used are  $1 \text{ mm}^2$ , 1 second and  $1 \text{ second}^{-1}$  respectively. The merit factor indicates the ratio of the sensitivity of the detector concerned to that of the ideal receiver. The maximum merit factor at room temperature can therefore only be unity. Higher values can only be obtained by working at lower temperatures, when the fluctuation energy  $kT/2$  is smaller. Naturally, this valuation of various types of radiation detectors is arbitrary to some extent. For this reason new research has been undertaken recently to arrive at a better solution of the problem.<sup>80,81,82,83,86</sup>

According to Jones, at a measurement time of 1 second and with a receiving area of  $1 \text{ mm}^2$ , the thermodynamic limit at room temperature determined by the fluctuation flux, is  $3 \cdot 10^{-12} \text{ watt}$ .<sup>82</sup> A similar value has been given at an

earlier date by Bauer in a different form. He calculated an irradiance of  $2 \cdot 10^{-8}$  watt/cm<sup>2</sup>  $\pm$  1 per cent.<sup>26</sup> Conversion to mm<sup>2</sup> and fluctuation flux gives the factor  $10^{-4}$ , which is the numerical difference between Jones's and Bauer's figures. This theoretical limit has been very nearly reached in practice.

## 6. Applications

The non-selectivity of thermal detectors is important in every case where the radiation must be measured independently of its wavelength. In the far infra-red we have anyhow no choice. A further advantage of thermal detectors is that they are less sensitive to irregularities in the irradiance since for them only the absorbed heat is the decisive factor.

Both thermo-couples and bolometers are available with very small, rectangular receiving surfaces (e.g.  $0.1 \times 10$  mm<sup>2</sup>). These are termed linear thermo-couples or linear bolometers. These detectors are usually designed as vacuum detectors and have therefore a higher sensitivity. They are particularly useful for the measurement of rectangular radiant surfaces, as for instance the slit of a spectral instrument.

Thermopiles and bolometers with larger receiving surfaces usually operate at normal air pressure and are used mostly for measurement in the field of radiation. With regard to irradiance, their larger receiving surfaces render them more sensitive than the considerably smaller linear detectors, even when the latter operate *in vacuo*. This does not apply, however, when the sensitivity is related to the radiant flux.

## IX. PHOTOELECTRIC RADIATION DETECTORS

### 1. Principles

All photoelectric detectors are based on their property of releasing electrons by absorption of radiation, which here can be considered as quanta with energy  $h\nu$ . In the external photoelectric effect the electrons are released from the surface into the ambient atmosphere (vacuum or gas), while in the internal photoelectric effect the electrons released move in the structural lattice.

In all cases it is necessary to produce a certain minimum energy, the release energy  $A$ , which at the same time determines the long-wave limit  $\lambda_R$ .<sup>4,5,6,13</sup> If the corresponding boundary frequency is  $\nu_R$ , we have according to equations (1) and (2):

$$\nu_R = A/h; \quad \lambda_R = ch/A \quad (41)$$

In the most favourable case, each quanta of radiation releases one electron. The quantum yield (number of released electrons divided by number of quanta) is then 1. Even at the same quantum yield, a given radiation energy will release fewer electrons when the wavelength is shorter. In practice, the quantum yields are mostly well below 1; moreover, the actual values will depend also on the wavelength.

*There exists a strong dependency on wavelength in total photoelectric yield, i.e. the number of released electrons divided by the liberating radiation energy. Photoelectric receivers are therefore very selective. The only way to encompass a large wavelength region is by combining different suitable photosensitive materials.*

The above mentioned limit to the long wavelength side of the spectrum cannot be extended at will, because a material with very small release energy easily liberates electrons by absorption of heat from the surroundings.

### 2. Photo-cells and photo-multipliers

These depend on the external photoelectric effect, particularly of the alkaline metals sodium, potassium and caesium.<sup>13,111,157</sup>

With photoelectric cells, the radiation falls through a wire gauze or ring electrode on a light-sensitive layer forming the other electrode. The ring or wire gauze electrode has a positive potential of about 100 volts above that of the layer, and serves therefore as anode, so that the electrons released by irradiation of the cathode layer move to the anode. In another design, the radiation passes through the light-sensitive layer, which in this case is extremely thin, and falls on the anode behind the photo-cathode. Both layer and anode are enclosed



in a glass or quartz envelope, which is either evacuated or filled with a suitable gas at low-pressure (see Fig. 57).

The number of electrons released per unit time is proportional to the incident radiation flux over a wide range. In the case of vacuum cells no further charge carriers are present, the intensity of the cell current will also be proportional to the radiation flux, provided of course that the anode voltage is sufficiently high to ensure that all electrons reach the anode. The cell must therefore work at the saturation point.

In the case of gas-filled cells, additional charge carriers are produced by the bombardment of gas molecules by the electrons; the current is therefore higher than in a vacuum cell. There is an optimum value for the anode voltage

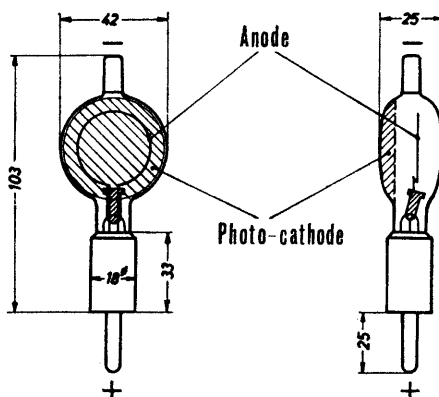


Fig. 57 Photoelectric cell with ring anode (vacuum).

at which the current is not too strongly dependent on the voltage. At higher anode voltages complete ionization takes place with a gas discharge, so that the current intensity is independent of the electron-releasing radiation (see Fig. 58).

It is obvious that because of the reciprocal action between the originally released electrons and the gas molecules, the proportionality between radiation flux and cell current is not found to the same high degree as in vacuum cells. Gas-filled cells are therefore more suitable as sensitive detectors, while vacuum cells are best for measurement purposes. But here, too, for measurements of very high precision special cells are required. If one has to use mass-produced cells, it is often possible to select a suitable specimen from a large number.

Fig. 59 shows the relative spectral sensitivity of photo-cells having different cathode materials.

Because the currents are too small for direct measurement and because the internal resistance of photoelectric cells is very high, of the order of megohms,

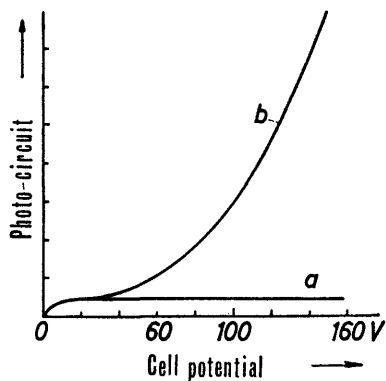


Fig. 58 Current-voltage curve of a photo-cell at constant radiation intensity. (a) vacuum cell; (b) gas-filled cell.

it is normal practice to connect a resistance of comparable value in series and measure the potential drop across this resistance. This is done with an electrometer or valve electrometer, if necessary with balancing potential connected in opposition. A good method is to connect the compensating potential in series

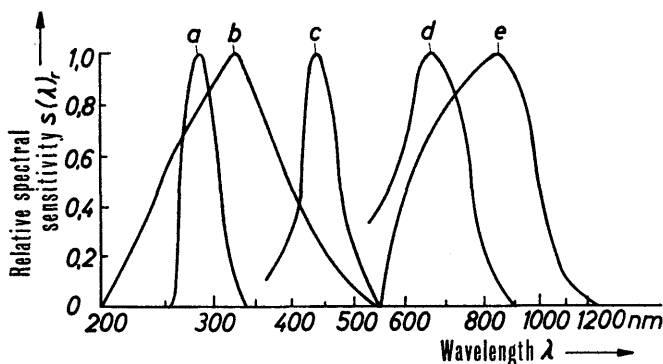


Fig. 59 Relative spectral sensitivity of photo-cells. (a) cadmium cell; (b) sodium cell; (c) potassium cell; (d) caesium-potassium cell; (e) red-sensitive cell.

with the cell potential; in this way the potential across the photoelectric cell will remain unchanged (see Fig. 60).

These high resistance values demand high insulation. Working with photo-electric cells may be thought to be inconvenient for this reason.

*Manufacturer: Mullard; Vakuumtechnik G.m.b.H.*

This drawback can be avoided by the use of a secondary emission multiplier.<sup>34,44,58,167</sup> Here, the electrons released from the photo-cathode by the radiation first strike an auxiliary electrode which itself has no photoelectric sensitivity. Secondary electrons are ejected from the electrode by the impinging primary electrons. The former then travel to the next auxiliary electrode, where the process is repeated. The result is a very high overall amplification of the original photo-current. Naturally, each successive electrode must have

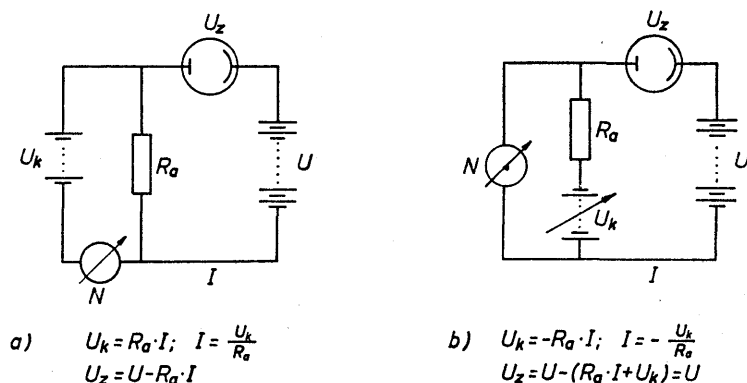


Fig. 60 Measurement of the photoelectric cell current by compensation. (a) cell potential  $U_z$  is reduced by the potential drop across  $R_a$ ; (b) cell potential  $U_z$  is constant and equals  $U$ .

$U$  = supply voltage,  
 $U_z$  = cell potential,  
 $U_k$  = compensation potential,  
 $R_a$  = outer resistance,  
 $I$  = photo-current,  
 $N$  = Null instrument (galvanometer, electrometer, valve electrometer).

a successively increasing positive potential, so that a very considerable total potential of between 1,000 and 2,000 volts is required. Up to a dozen auxiliary electrodes can be used and the multipliers are capable of producing at the final anode a current which can be measured with an ordinary instrument of low resistance, e.g. a galvanometer. As with ordinary photoelectric cells, compensation can be applied in this case as well and the previous remarks on compensation are valid for photo-multipliers (see Fig. 61).

The main difficulty in using photo-multipliers is the necessity for the above-mentioned high voltage, which is distributed to the different steps by a potential divider. High stability is required. The thermionic current is highly sensitive to changes in potential; the multiplication is proportional to a power of the total voltage. Very carefully stabilized power packs are therefore essential, as battery operation would be too cumbersome and too expensive in the long run.

As stability of the electrode voltages is very difficult to obtain to the desired accuracy, the photo-multiplier is not very suitable for the measurement of absolute values. In practice, only voltage stability over short periods of time

will be required if the multiplier is used for the measurement of relative values only.

A small dark current will occur even when no radiation takes place, because of the thermally released charge carriers. This dark current can be quite considerable in the case of red-sensitive cathodes. For measurement purposes, this dark current must always be subtracted.<sup>158,159,175</sup> It is possible to restrict

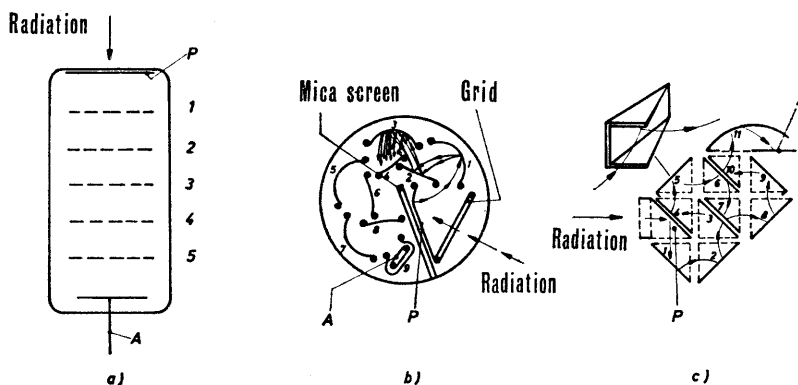


Fig. 61 Photo-multiplier. (a) wire gauze electrodes; (b) plate electrodes; (c) door electrodes. P = photo-cathode; A = anode; 1-11 = auxiliary electrodes.

the deviation from proportionality to incident radiation to approximately 1 per cent within a current range of 3 to 4 powers of ten.<sup>75,98,127</sup> But for this it is necessary to select the best specimen from a number of multipliers.

When the required degree of accuracy is not very high, working with photo-multipliers is very convenient. They enjoy an ever increasing popularity for many purposes.

*Manufacturers: Dr. Georg Maurer; E.M.I. Electronics; Mullard; Radio Corporation of America.*

### 3. Barrier layer photovoltaic cells

It is well known that an electric field will be produced at the junction between two semi-conductors, or between metal and semi-conductor, as a result of the respective positions of charges and their energy levels. This field causes the electrical resistance of the junction to be dependent on the direction of current and explains why we speak of a barrier layer. Contacts of this type are found in barrier layer rectifiers.

When electrons in the barrier layer are released by radiation, they will move under the influence of the electric field. In this way, the charge on one side of

the barrier layer will be increased; a so-called photo-e.m.f. is produced.<sup>11,13</sup> The phenomenon itself is called "barrier layer photo-effect."

Closing the circuit through an external resistance, a photo-current will ensue. A photovoltaic cell is characterized by the value of the photo-e.m.f. when the current is zero (the no-load voltage)—and by the current when a low resistance is connected in the external circuit (the short-circuit current).

Various materials are suitable for the manufacture of barrier layer photovoltaic cells; the most important are cuprous oxide and selenium.<sup>11,13,65,155,186</sup> The usual procedure is to coat an iron plate of about 1 mm thickness with selenium, with other additives, and apply heat treatment. The selenium layer is in turn coated with a thin transparent metal layer, through which the radiation

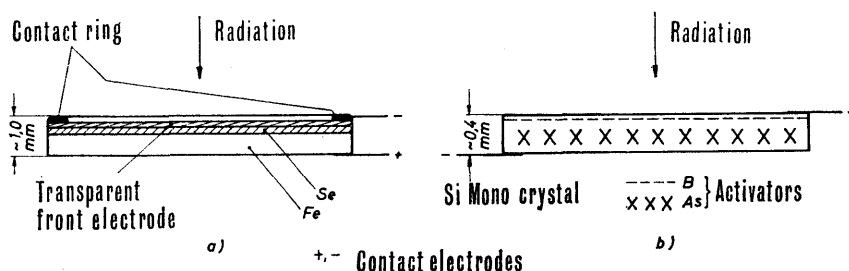


Fig. 62 Photovoltaic cells (B. Lange). (a) selenium cell; (b) silicon cell.

passes. Lattice screens are also used for this purpose. The current is taken from the iron plate and the transparent electrode (see Fig. 62a).

The main advantage of this type of cell is its high sensitivity which enables the photo-current to be measured with relatively insensitive pointer instruments. Furthermore, the short-circuit current is reasonably proportional to the radiation intensity. A wise precaution is to check the characteristics of a cell first and if necessary, to select the best specimen from a number.<sup>13,185</sup>

The degree of proportionality may, however, not be good enough for really high demands. Fatigue symptoms following long radiation periods may make it necessary to keep to a well-defined series of illuminated and dark periods.

Finally, selenium cells are capable of a change in sensitivity for a short period, after pre-irradiation of a different wavelength band, particularly the red.<sup>51</sup> Working with selenium cells makes the observation of a number of extra checks essential.

In recent times, the silicon cell<sup>184</sup> has gained in importance. The semiconductor here is silicon with a suitable activator, such as arsenic. The main characteristic of this cell is its high photo-current; its constancy is also excellent. Compared with the selenium cell, it has a considerably smaller internal resistance (about 50 ohms). Optimum proportionality between radiation flux and photo-current is sometimes obtained by using a higher resistance in the

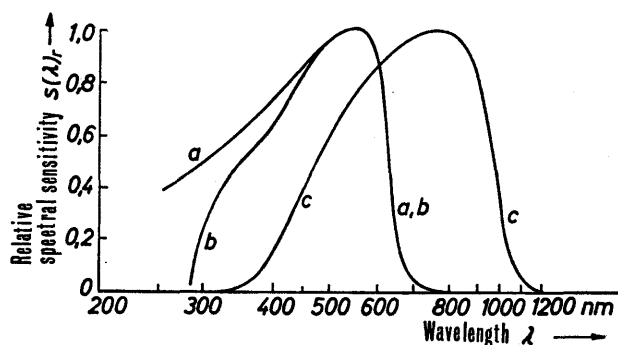


Fig. 63 Relative spectral sensitivity of various cells. (a) selenium cell with quartz cover disc; (b) lacquered selenium cell; (c) silicon cell.

external circuit and not, as in the case of the selenium cell, by a very small one (see Fig. 62b). Fig. 63 shows examples of the spectral sensitivity for various cells.

*Manufacturers: Electrocell G.m.b.H.; Evans Electroselenium; Dr. Bruno Lange; Megatron; Research Electronics; Weston Electr. Instr. Corp.*

#### 4. Photoconductive cells

Photoconductive cells are also based on the internal photoelectric effect.<sup>13,91,144,170</sup> The electric conductivity or the electric resistance of the substance concerned is changed under the influence of the photoelectrically released electrons. The change in resistance is then a measure for the incident radiation flux.

As the dark current, present when no radiation takes place, is not negligible, modulated light is often used to separate the photoelectric working current from the dark current. The A.C. current produced can then be measured using one of the standard methods of amplification.

Because of the lack of proportionality between photo-current and radiation flux, as well as some inconstancy of sensitivity, photoconductive cells can only be considered in special cases as measurement detectors. They can, of course, be used as comparators or null indicators. Their widest use is in the near infra-red, beyond  $1\ \mu$ , where other detectors are unsatisfactory.<sup>63</sup>

The substances used are lead sulphide ( $\text{PbS}$ ),<sup>85,171</sup> lead selenide ( $\text{PbSe}$ )<sup>118</sup> and lead telluride ( $\text{PbTe}$ )<sup>188</sup> which have photo-sensitivities out to more than  $4\ \mu$ . Another substance is cadmium sulphide ( $\text{CdS}$ ), whose long-wave limit is inside the visible spectrum (see Fig. 64).

Recently, photoconductive cells incorporating germanium or silicon (with the addition of suitable activators) have been produced, whose sensitivity can

sometimes extend beyond  $100\ \mu$ .<sup>192,193,194</sup> Equation (2) shows that at such great wavelengths, the corresponding quantum energy is so small that thermal excitation occurs at room temperature. Cooling (sometimes to below the temperature of liquid helium) must therefore be used to produce the required reduction in background excitation.

With regard to photoelectric detectors, mention should be made of the photodiode in which radiation causes a variation in the resistance, dependent on the direction of the current, as well as the phototransistor in which radiation causes charge carrier couples to be formed whose current is amplified. These detectors are however rarely used for measurement purposes. Generally speaking, we can assume that hand in hand with the progress in semi-conductor

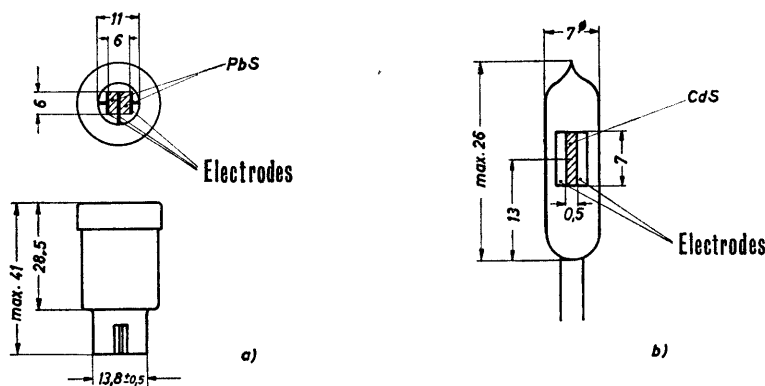


Fig. 64 Photoconductive cells. (a) lead sulphide; (b) cadmium sulphide.

techniques, many improvements in photoelectric detectors can be expected. An instance is the P.E.M. (photoelectric magnetic) receiver, where a photoelectrically produced electron—hole pair is separated by means of a magnetic field. Detailed experiences with this receiver are not yet available.

### 5. Sensitivity limits

The sensitivity limit for photoelectric detectors is determined by the heat energy in relation to the quantum yield and the long-wave limit. According to R. C. Jones, the disturbance radiation flux is approximately  $5 \cdot 10^{-19}$  watts for a measurement period of 1 second and a receiving surface of  $1\ \text{mm}^2$  at room temperature. This is considerably less (about  $10^7$ ) than with thermal receivers.<sup>80,86</sup> The sensitivity limit is normally more favourable at lower temperatures and in some cases the long-wave limit is extended as well. Simultaneous cooling of the receiver's housing is of particular importance in the case of detectors for the far infra-red. If this precaution is not taken, the sensitivity will be limited by statistic fluctuations in the temperature radiation of the surroundings (photon noise).

The indicated limit, which in the visible spectrum would correspond with approximately 1 radiation quantum per second, will not be approached even remotely. This behaviour is ascribed to spontaneous thermal electron-rejection processes.

*Nevertheless, photoelectric receivers are more sensitive in practice than thermal receivers in certain spectral regions. The difference may amount to several magnitudes.*<sup>49, 64, 79, 83, 126, 176</sup>

## 6. Applications

Photoelectric detectors and in particular the widely used photovoltaic cells and photo-multipliers, are mostly manufactured with large receiving surfaces, of the order of several cm<sup>2</sup> and require a correspondingly large radiation field.

It is not practical to form an image on a photoelectric detector because of the impossibility of producing a sufficiently large and uniform radiation field. Moreover, it is always better to make the irradiated area slightly larger than the detector surface.

Because of unavoidable unevenness of the photoelectrically sensitive material the sensitivity of photoelectric detectors from point to point on the surface is not uniform. Should the irradiated surface be smaller than the detector surface, even a small deviation from the correct adjustment may cause a considerable change in the photo-current, as a different part of the sensitive surface is then irradiated. Lack of homogeneity in the radiation field (i.e. irradiation intensities varying from point to point) have the same result.

Therefore, if it is required to make exact measurements with photoelectric detectors using an image focused on the detector, it is advisable to insert a diffusion disc at a short distance from the detector in the path of the rays. This ensures uniform irradiation intensity, but wastes part of the radiation, because the diffusion disc emits radiation in directions that do not reach the detector. Nevertheless, the great sensitivity of photoelectric detectors makes this loss in radiation acceptable.

Generally speaking, photoelectric detectors are used in all those cases when high sensitivity is an important factor and when the inherent selectivity is not a drawback or is possibly desirable. This is valid when it is desired to eliminate the action of certain spectral regions (especially infra-red) or to match certain response curves. For instance, various designs of detectors adjusted to the spectral sensitivity of the eye have been manufactured and these use photoelectric detectors.



## X. METHODS OF RADIATION MEASUREMENT

Before discussing radiation measurement in detail, let us consider a few general principles.<sup>1,4,5,6,13,14,16,21,57</sup>

### 1. *Relative and absolute measurements*

In many cases a knowledge of the relative values of radiations is sufficient. When determining the actual values (numerical value times the unit), we call these absolute values or absolute measurement. The term "conversion to absolute values" is used when the determination of a single absolute value changes a number of relative values into absolute values.

Absolute radiation values can be obtained in two different ways:

- (a) by means of a detector of known spectral sensitivity (see VII, 3);
- (b) by means of a radiator of known spectral emission (see II, 3).

The spectral sensitivity of a detector can be determined by comparing the radiation energy with an electrical, thermal, or other directly measured form of energy. Such a measurement is however only possible with special detectors, not suitable for general use. But the spectral sensitivity of a given detector can then be obtained by comparison with such an "absolute" detector.

The spectral emission of a radiator can so far only be established in absolute terms for a black body radiator, being fixed for the latter by the indication of the radiator temperature, according to equation (24). The spectral emission of a given radiator can thus be obtained by comparison with a black body radiator.

When a detector of known spectral sensitivity is available, it can be used to measure the spectral emission of a radiator, and vice versa. The basic requirement, therefore, is the possession of either a detector or a radiator of known properties.

As the determination of the sensitivity of a detector by comparison with an electrical, thermal, or other form of energy is very difficult, the detector will only be used for basic measurement, e.g. for the experimental proof of Planck's radiation formula. Moreover, as a rule the time constancy of detectors is not as good as that of radiators.

For these reasons, the starting point in measurement practice is the radiator, either a black body radiator or a tungsten lamp calibrated against a black body radiator.

### 2. *Detectors of known spectral sensitivity*

All such detectors are thermal detectors. The spectral sensitivity is then defined by the degree of spectral absorption  $\alpha(\lambda)$  of the blackening of the

radiation receiving surface. This value should be as independent of the wavelength as possible. The detector should therefore be at least grey; the ideal being to reach black (when  $\alpha = 1$ ).

(a) Calorimetric measurement

Radiation is received in an internally blackened hollow sphere, so that practically all radiation is absorbed. A certain minimum reaction time is required to obtain a measurable amount of energy. The radiation flux normally available is usually small, so that a long measurement time is required in accordance with the relatively low sensitivity of calorimetric measurement methods. This makes the process time-consuming and inconvenient. The method is therefore only practised when large radiations are available, as for example is the case when measuring the radiation of the sun.

(b) Electrical measurement

Electrical measurement is more favourable, particularly because one does not measure the energy itself but determines the flux immediately. The difficulties in measuring heat energy cannot be avoided, however.

In this case the detector consists of a blackened thin metal foil. Any residual radiation reflected by the foil is reflected back to the foil by a hemispherical mirror in whose centre of curvature the foil is placed. This makes that the degree of absorption  $\alpha$  is practically equal to unity. The radiation falls on the foil through a central hole in the mirror (see Fig. 49).

The increase in temperature which occurs during radiation and when a state of equilibrium obtains, is measured in any desired units. The radiation is then stopped and the foil is electrically heated to such an extent that the same rise in temperature is obtained. When the heating of the foil takes place in exactly the same way for both radiation and electric current, the electrical energy equals the radiation energy. By choosing a sufficiently thin foil, the period of time necessary to establish balance need not be long—of the order of a few seconds.<sup>56, 57, 69, 124, 152</sup>

In both cases (a) and (b) the observation of a number of additional conditions will be required when accuracy of measurement is required.

In practice, one of the usual non-selective thermal detectors (thermocouples, thermopiles or bolometers) are employed, the sensitivity of which is determined by means of one of the described detectors or of a radiator of known emission. Practice has shown that the sensitivity of these thermal detectors is of good constancy. It is true that in the course of time a change in the degree of absorption (and thereby in the sensitivity) can occur because of changes in the black coating through flaking, structural changes, etc. Frequent checks are therefore recommended.

In theory, photoelectric detectors may also be used. But their selectivity

complicates the evaluation of a measurement. As the constancy is also suspect, these detectors are only used in special cases.

As the spectral sensitivity of every thermal detector is determined only by the wavelength response of the blackening substance, only by measuring the latter can a detector of known spectral sensitivity be established. When the blackening is satisfactory, the spectral sensitivity will be constant and the relative spectral sensitivity be unity (see VII, 3).

There is no corresponding measurement possible with photoelectric detectors. Neither is it possible to obtain accurate information with regard to the spectral dependency of the photo-effect by other means. Thermal detectors must be used to establish this data.

### 3. *Radiators of known spectral emission*

The black body radiator is also inconvenient in practice. Incandescent lamps will mostly be used, the emission of which can be determined by comparison with a black body radiator or a detector of known spectral sensitivity.

We should note that the radiation of an incandescent lamp comes from both the hot lamp envelope and the filament itself, and these temperatures will be very different. Moreover, the temperatures are never exactly the same for different elements of the filament and the bulb. We cannot, therefore, speak of a single spectral radiance; the spectral composition of the radiation will only be constant for distances greater than a certain value.

This is not serious when measuring the total radiation by means of carbon or, more recently, tungsten filament lamps, as for instance the Osram Type Wi 40 lamp. But when spectral analysis of a radiation is desired, it is much better to limit oneself to a certain part of the filament lamp in order to obtain uniform radiance.

Tungsten ribbon lamps are very suitable for these purposes. Their design is such that a rather large surface has uniform temperature and therefore uniform radiance.

It is also possible to determine a distribution temperature in the visible spectrum with a tungsten ribbon lamp, thus yielding the relative spectral radiation distribution.

Another possibility is to calculate the spectral radiation distribution from the true temperature of the tungsten ribbon, and the spectral emissivity. The temperature is measured from a distance with a pyrometer, but the spectral transmission factor of the lamp envelope or window must be known. This method is not recommended for exact measurements because the values of emissivity can be slightly different for different specimens of tungsten ribbons.

Even by the most careful treatment and avoidance of all overloading, every filament lamp suffers an unavoidable deterioration. The best method, therefore, is to use several such lamps during any reasonable period and distribute the

work evenly among them. Some will be used for regular work and compared with unused lamps at regular intervals of approximately one year.

In the past, the Hefner lamp<sup>4</sup> was often used for measuring total radiation. This lamp is a flame of specified dimensions burning amyl acetate. It was used as a standard lamp for luminous intensity; hence the old unit, the Hefner candle. These lamps, however, are inconvenient in use and not very exact. They are hardly ever used at the present time. All the same it can be worth knowing that the intensity produced by the total radiation of a Hefner lamp at a distance of 1 metre amounts to approximately  $95 \mu\text{W}/\text{cm}^2$ .

The temperatures which can be reached in practice with both black body radiators and incandescent lamps only yield a very restricted emission in the ultra-violet band, so that such measurements would be difficult. Radiators which are more efficient in the UV band have therefore been designed, e.g. the UV standard lamp (see IV, 3). But we must point out that the radiance of the UV standard lamp is only uniform over most of the length of the discharge, while a certain drop occurs from the centre to the sides of the discharge. As this drop of radiance depends on wavelength, the spectral distribution will also be altered according to the distance from the centre line of the radiator.

A radiator whose relative spectral emission can be calculated from other factors, does not exist. The relative spectral radiation distribution of the tungsten ribbon lamp in the visible spectrum as shown by distribution temperature must also be determined with reference to the radiation from a black body.

#### 4. *Measurement of radiators*

To measure a radiation, one can start from either a detector of known sensitivity or a radiator of known characteristics. The following possibilities are therefore available:

##### (a) *Measurement with detector of known spectral sensitivity*

*Total radiation.* To measure the total radiation, the value of the total sensitivity, as defined in equation (38) is required. When a selective detector is used  $(E_\lambda)_r$  (equation 38a) should at least be known. Equation (38c) shows that this is not necessary in the case of a non-selective detector. Generally speaking, measurement of total radiation can therefore only be effected with non-selective detectors.

*Measurement of spectral radiation.* In this case a narrow spectral band must be isolated by means of a monochromator or filter. For this only the appropriate single spectral sensitivity is used for calculations and measurement with both selective and non-selective detectors is possible. To form an opinion of the conditions in the radiator itself from the measured values, the spectral transmission factor of the monochromator or filter and the optics of the assembly

must be taken into consideration. This is especially important when working with an optical image.

(b) Measurements with radiator of known spectral emission

Here the principle is to determine first the sensitivity of the measuring unit with the known radiator and immediately after to measure the unknown radiator. As the sensitivity of the complete measuring system is the same for the evaluation of both measurements of radiators the method amounts to a direct comparison between the two radiators.

We require from the detector an indication proportional to radiation flux and constancy of sensitivity, at least for the period required for the measurement.

*Total radiation.* In order to determine the overall sensitivity according to equation (38) by measurement with a known radiator, it is also necessary to know the spectral sensitivity of the detector. When a selective detector is used, knowledge of the relative spectral radiation distribution of the radiator to be examined is also necessary (see equation (38a)). In the case of a non-selective detector, this condition does not apply (see equation (38c)). In general, only measurement with a non-selective detector is possible.

*Measurement of spectral radiation.* Once more, a monochromator or filter is used to isolate a defined small spectral region. For the reason mentioned under (a) we can use both selective and non-selective detectors. As the measurement assembly is the same for both radiators, no further data is required of them, not even the spectral transmission factor.

## 5. Measurement of detectors

The measurement of detector sensitivity has already been discussed to a certain extent when the measurement of radiators was described.

(a) Measurement with detectors of known spectral sensitivity

This measurement is based on first measuring the unknown radiation and immediately afterwards the unknown detector sensitivity. The radiation value is not needed in the evaluation, because we are only concerned with a comparison between both detectors.

Radiators must have constant emission for at least the period of measurement.

*Non-selective detectors.* When the radiation under measurement extends over a wide spectral region, a non-selective comparison detector must be chosen, whereas in the case of monochromatic radiation, a selective comparison detector may be used. When measurement of radiation of a wide spectral region is effected with a selective comparison detector, the relative spectral radiation distribution must be known (equation (38a)). As a rule, only non-selective comparison detectors should be used.

*Selective detectors.* The only requirement here is that the radiation under

measurement be spread over a sufficiently small wave-band. In this case, the comparison detector can be either selective or non-selective.

(b) Measurement with radiators of known spectral emission

*Non-selective detectors.* According to equation (38c) the radiators used for the measurement do not have to meet additional requirements for spectral radiation distribution. It is here sufficient to use a radiator of known total radiation.

*Selective detectors.* Apart from a radiator of known spectral emission, one needs a monochromator or filters to produce narrow-band radiation. It will be necessary to know the spectral transmission factor of either and the optical properties of a monochromator. It is then possible to determine the monochromatic irradiation at the position of the detector and hence the sensitivity of the latter.

It is always best to measure spectral properties by comparison as described above (4b and 5a). Then there is no need to know the spectral transmission factor of the equipment.

We should perhaps refer to the rather obvious fact that in general no absolute values of the other parameters are needed for the measurement of relative values. This makes measurement much easier in practice. In such cases the optical properties of the equipment do not play a part, provided they do not change the spectral composition of the radiation. A radiator, the spectral emission of which is to be compared with that of another radiator, may therefore be placed at an entirely different distance from the detector than the comparison radiator. It is also permissible to position two detectors, the performances of which are to be compared at completely different points in the field of radiation.

## 6. Additional information

### (a) Spectral measurement

With regard to spectral measurements, the whole technique depends upon the isolation of a sufficiently narrow wave-band  $\Delta\lambda$ . A corresponding value for the radiation will then be obtained, e.g. radiation energy  $\Delta Q$  and a value for the detector reading  $\Delta I$ -valid for the selected wavelength  $\lambda$ . The magnitudes for the spectral properties  $dQ/d\lambda$  or  $dI/d\lambda$  to be determined can then be calculated approximately by means of the difference quotients  $\Delta Q/\Delta\lambda$  and  $\Delta I/\Delta\lambda$ . The smaller  $\Delta\lambda$  is, the better the approximation. But as the radiation energy decreases with  $\Delta\lambda$ , the limits are set by the amount of energy available.

Strictly speaking, in each spectral measurement we deal therefore with quotients of small quantities, which however do not have to be very small in practice. The very narrow wave-band emission of a spectral line contains very considerable energy and results in a correspondingly large reading on the

instrument. This is normally expressed by omitting the difference symbol  $\Delta$ . Nevertheless it is useful to keep the true state of affairs in mind.

A spectral measurement becomes critical when the quantity to be measured changes so rapidly with the wavelength that it is no longer possible to assume proportionality to  $\Delta\lambda$ . In such circumstances a correction must be made (see VI, 3).

Similar considerations enter into the emission measurement of a spectral line, whose spectral radiation distribution it is impossible to determine in the way described, because the wavelength band-breadth available in monochromators is too great. All we can do is to measure the total emission of a line.

#### (b) Radiation attenuation

As many detectors show a linear intensity response only over a restricted range, the radiation must often be attenuated. Attenuation of the more intense flux can frequently be adjusted so as to make two radiation fluxes equal. This enables them to be compared by a method requiring only a comparison detector (VII, 1) and is particularly useful for recording instruments. The setting of the attenuating device is a measure of the flux.

Such attenuation can be attained in one of the following ways:

*Inverse square law.* According to equation (9b) the irradiance changes with  $1/r^2$ . When a sufficiently nearly point-like source is used, changing the distance between radiator and detector will be accurate enough for changing the irradiance quantitatively. Errors can be introduced in the infra-red band by carbon dioxide and water vapour present in the air. In all regions, losses which increase with  $r$  can be caused by scatter by dust, smoke or fog.

*Filters.* Attenuation is also possible by non-selective (neutral or grey) filters, the transmission factors of which have been measured beforehand. The transmission factor depends a little on the relative aperture of the pencil of rays going through them, because the length of path through the filter is long, the more inclined the ray is to the normal.

*Polarization.* The intensity of linear-polarized radiation can be changed quantitatively by inserting an analyser at different angles in the path of the radiation. A drawback is the very considerable loss when the radiation is polarized in the first place. Furthermore, the transmission factor has no linear relationship with the angle of rotation  $\epsilon$ , but changes with  $\cos^2 \epsilon$ . Finally, polarization of the radiation is often a drawback.

*Wire screens.* Wire screens of different mesh sizes will also attenuate radiation. The dependency on wavelength of the transmission factor is very small, but cannot be ignored in the long-wave part of the spectrum. This dependency is caused by diffraction.

*Rotating sector.* A rotating sector with fixed or adjustable sector has an average transmission factor equal to the ratio of the sector angle to  $360^\circ$ . The rotating sector may be placed at any position in the path of the radiation,

provided the complete pencil of rays is interrupted by the sector. It must be noted that only the time-average value of the radiation will be reduced, while the maximum value will remain unchanged. When additional modulation of the radiation and measurement with A.C. methods are used, serious difficulties may be introduced by "beating" between sector frequency and modulation frequency. This method has therefore very limited application.

*Aperture diaphragm.* An adjustable diaphragm positioned in a uniformly illuminated pupil, e.g. that of an image-forming lens (see Fig. 42) transmits a radiation flux that is proportional to the aperture area.

#### (c) Interchanging radiators and detectors

When two radiators or two detectors are measured by comparison, the best way is to effect a direct exchange, for example by means of a sliding carrier. As this method is sometimes inconvenient and often hardly possible for technical reasons, the beam of radiation can be appropriately directed by a rotatable mirror. For measurements of great accuracy it is however necessary to check that the spectral reflection factor of the mirror is the same for both positions.

#### (d) Special occasional techniques

We have already mentioned (VII, 2) that what determines the response of a detector is the irradiance.

With the radiator at a given minimum distance from the detector and working without image formation, the radiation intensity can be calculated from equation (9b). With image formation, however, equation (34), which is generally valid in the case of image formation, will give the radiance. If the measurement is not carried out by comparing radiators, the transmission factor of the image-forming lens must be taken into account.

Radiators with non-uniform radiance can be measured by irradiating a non-selective and diffusely reflecting or transmitting auxiliary surface (e.g. magnesium oxide or ground-glass) and by imaging this surface. The radiance of the auxiliary surfaces being measured, the irradiance falling on them can be determined. The radiant intensity of the radiator under examination is thus obtained. Should the measurement not be made by comparison of radiators, validity of Lambert's law for reflection or scattering at the auxiliary surface must usually be taken for granted. It is also necessary that the ratio of reflected or transmitted radiance to the incident irradiance, the so-called "radiance factor" is known. The loss in effective radiation transmission is considerable, however.

This method may give the impression of being rather complicated. But it should be used for instance when it is required to measure the spectral radiation distribution of a large type of radiator with non-uniform radiance by means of a monochromator. For in this case it is hardly possible to image the entire radiant surface on to the entrance slit. Moreover, the irradiation of the slit



area is not uniform; this can be involved with any peculiarities in transmission of the monochromator. But if such an auxiliary surface is used and imaged, each single spot of the radiant surface of the radiator contributes in the same way to the irradiation on the slit, which is accordingly equivalent to both the quantity and the spectral distribution over the entire surface.

# XI. MEASUREMENT OF SPECTRAL EMISSION OF RADIATORS WITH THE MONOCHROMATOR

## 1. Introduction

Let us first consider a few aspects of the output radiation through the exit slit of a monochromator.

We have already seen in Chapter V that a spectral line yields a practically monochromatic image of the entrance slit, while a continuous spectrum gives a set of overlapping monochromatic images. With equal dimensions of all slits, an equal-energy spectrum produces a triangular spectral radiation distribution in the exit slit.

For the following considerations, a single spectral dispersion is assumed, while the entrance slit is imaged on the exit slit without change of size. Disregarding losses, equation (34) gives us the same value for the spectral radiance for the radiator, the entrance slit and the exit slit. By taking into account the appropriate transmission factor, the losses in radiation can be calculated.

### (a) Line radiators

If the radiator line under observation has a radiant density  $L(\lambda)$ , to which can be ascribed a wavelength  $\lambda$  (by disregarding the very small actual width of the

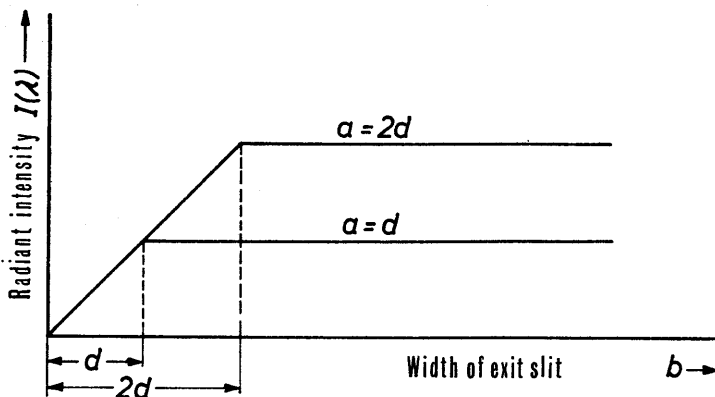


Fig. 65 Radiance in exit slit as a function of its width for a spectrum line.  $a$  = width of entrance slit.

line) and the width of the entrance slit is  $a$ , its height  $h$ , then a same-sized image will be produced in the area of the exit slit, radiating at the unchanged radiance  $L(\lambda)$  under the given conditions.

When the monochromator is adjusted to the wavelength in question, this

image will lie in the centre of the exit slit of width  $b$ , which should have the same height  $h$  as the exit slit. The outlet slit can then be closed to width  $a$ , without obstructing the radiation. Only when the slit is made still narrower will the radiation be obstructed and the emerged flux be reduced.

This means that radiant intensity  $I(\lambda)$  in the exit slit at first has the constant value  $L(\lambda)ah$ , which, for  $b < a$ , decreases linearly with  $b$  because the exit slit then cuts off part of the radiation (see Fig. 65).

$$I(\lambda) = L(\lambda)ah \text{ for } b \geq a; \quad I(\lambda) = L(\lambda)bh \text{ for } b \leq a \quad (42)$$

If there should be a group of lines so close together that the instrument cannot separate them properly, the exit slit can be opened up so that all the lines of the group appear in the exit slit. The radiant intensity is then equal to the sum of the individual intensities:

$$I = I(\lambda_1) + \dots + I(\lambda_n) = [L(\lambda_1) + \dots + L(\lambda_n)]ah \quad (42a)$$

Naturally, the radiance is not uniform over the exit slit in this case.

#### (b) Continuous radiator

The radiator under consideration is supposed to have a constant spectral radiance  $L_\lambda$  for such wavelength interval as may be in question. This case will never occur in practice, but if the spectral radiance changes linearly with wavelength, the quantities we are interested in involve a mean value for the radiance. For small wavelength intervals, as are discussed here, it is permissible, of course to assume this linear relation.

A continuous spectrum is produced in the area of the exit slit, consisting of overlapping monochromatic images of the entrance slit, each individual image having the same spectral intensity  $L_\lambda$ . The area of the slit is  $ah$ . The spectral radiant intensity of such a monochromatic image will then be:

$$I_\lambda = L_\lambda ah \quad (43)$$

In order to calculate the total radiant intensity  $I(\lambda)$  in the exit slit (to which should be given a mean wavelength value  $\lambda$ ), we simply multiply by the effective wavelength interval, namely the spectral slit width  $\beta$  and obtain, according to equation (30b):

$$I(\lambda) = I_\lambda \beta = L_\lambda hab / D(\lambda) \quad (44)$$

The radiant intensity in the exit slit therefore also increases linearly with the product of the slit widths in the case of a continuous spectrum (see Fig. 66).

The radiant intensity per unit area  $L(\lambda)$  in the exit slit can be directly calculated from this equation by division by the area  $hb$  of the exit slit:

$$L(\lambda) = I(\lambda)/bh = L_\lambda a/D(\lambda) = L_\lambda \alpha \quad (45)$$

where  $\alpha = a/D$  from equation (30b), the wavelength interval in the exit slit corresponding with the width of the entrance slit.

It is true that the radiant intensity per unit area  $L(\lambda)$  is composed for each point of the exit slit of contributions of slightly different wavelength regions, but the value itself is constant throughout.

The relations become a little more complicated in the case of multiple spectral dispersion. However, when the most usual condition, namely that all slits are of the same width, is met, the derived corrections can be used in the form given. Identical width of all slits is the most favourable solution with regard to spectral purity and quantity of transmitted radiation flux.

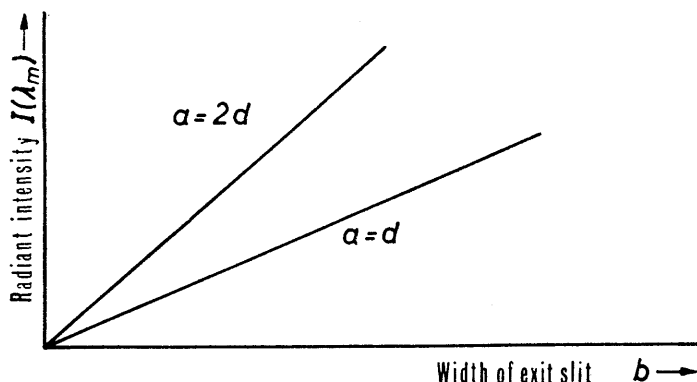


Fig. 66 Radiant intensity in the exit slit in relation to its width (continuous spectrum).  $a$  = width of incident slit.

Taking into account the curvature of the slit images, we arrive at a slightly different condition for line spectra. Two possibilities present themselves:

- (1) the entire radiation flux passes through the monochromator:  
entrance slit < central slit < exit slit (Fig. 67a)

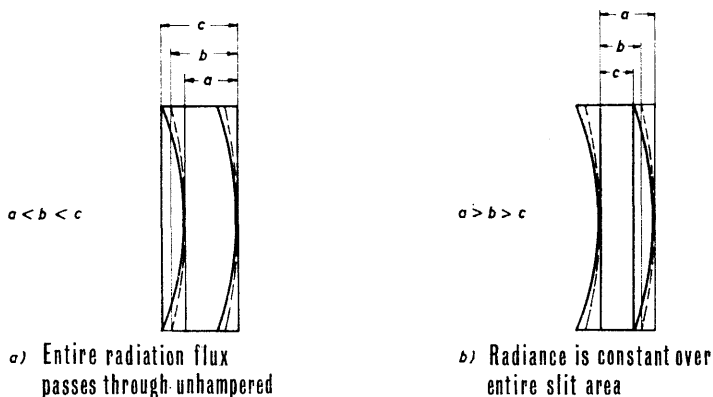


Fig. 67 Most suitable slit widths of a spectral line, considering the curvature of the slit images.  $a, b, c$  = widths of entrance, central and exit slits.

- (2) the exit slit shows uniform radiance over the entire area:  
entrance slit > central slit > exit slit (Fig. 67b)

The relations thus described in simplified form can be further modified by the curvature of the slit images and by the image aberrations. They represent therefore an approximation.

(c) Transmission factor

The spectral transmission factor of the monochromator, for which the arbitrary value 1 has been implicitly chosen, only enters the calculations as a coefficient (in common with the magnification) and can be taken into account afterwards.

We should mention that one often distinguishes between material transmission and slit transmission of a monochromator.<sup>28</sup> The material transmission is determined by absorption, reflection and scatter occurring in all optical elements, while the so-called slit transmission takes into consideration the variation of dispersion of the continuous spectrum at different points in the

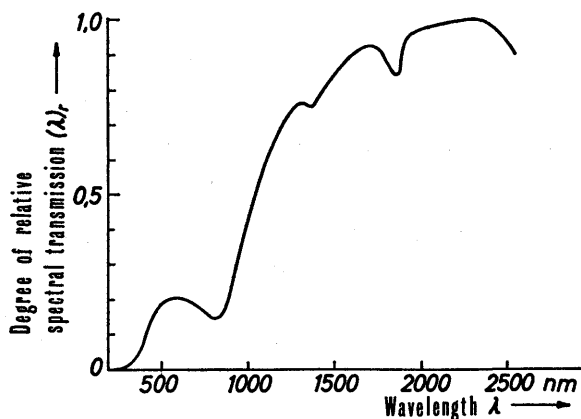


Fig. 68 Spectral transmission of a double monochromator, including optical means for image formation (quartz prisms, aluminized mirrors).

spectrum. As this is discussed separately, we mean by the transmission of a monochromator simply the material transmission as specified by the spectral transmission factor (see Fig. 68).

The transmission can be determined by taking as radiator a monochromatically illuminated slit, which can also be the exit slit of an additional monochromator. We now measure both the radiation flux  $\Delta\Phi$  entering the monochromator under examination and the radiation flux  $\Delta\Phi_r$  emerging from the monochromator. The quotient  $\Delta\Phi_r/\Delta\Phi$  yields the degree of spectral transmission  $\tau(\lambda)$  for a wavelength interval  $\Delta\lambda$ , adjusted on the monochromator.

It is recommended that the optical means for image formation used before

and after the exit slit be taken into account, because they can be a source of additional losses of radiation. By a suitable choice of slit width, one can ensure that the incident pencil of rays passes through the monochromator without losses due to vignetting. Furthermore, we should take care that the effective aperture of the monochromator is fully illuminated, as by using in effect a smaller relative aperture other transmission values sometimes result.

Purely relative values of the spectral transmission factor can be obtained by means of a radiator of known relative radiation distribution, e.g. a black body radiator or, in the visible spectrum, a tungsten ribbon lamp of known distribution temperature and a non-selective detector. If the detector reading  $I(\lambda)$  and the relative spectral radiant intensity per unit area of the radiator is  $L(\lambda)_r$ , then the required relative value  $\tau(\lambda)_r$  is determined by the quotient  $I(\lambda)/L(\lambda)_r$ .

#### (d) Monochromator and detector

To the detector following the monochromator, the exit slit represents the source of radiation, which emits a radiation of a given radiance  $L$  at the aperture angle determined by the monochromator and the image. How this radiance is formed and to what degree it is uniform for the slit, depends on the conditions before and inside the spectral instrument.

When the radiance in the exit slit is uniform, the following simple relationship exists:

*Without image formation*, an irradiance  $E$  is produced according to III, 2, equation (9b), because the radiant intensity  $I = Lbh$  at slit area  $bh$  according to equations (42) and (45):

$$E = I/r^2 = Lbh/r^2 \quad (46)$$

where  $r$  = distance between exit slit and detector.

The irradiance therefore increases linearly with the slit area.

*With image formation*, however, we find according to VIII, 5, equation (9c) the irradiance  $E$ :

$$E = Lf_s/r^{*2} \quad (47)$$

where  $r^*$  = distance between image-forming means and detector;

$f_s$  = effective area of image-forming means.

The irradiance is here independent of the slit area.

In the case of a group of lines and when the exit slit is wider than the entrance slit ( $b > a$ ) in order to encompass the entire group of lines, we find, using equation (42a):

*Without image formation*

$$E = \{I(\lambda_1) + I(\lambda_2) + \dots I(\lambda_n)\}/r^2 = \{L(\lambda_1) + L(\lambda_2) + \dots L(\lambda_n)\}ha/r^2 \quad (46a)$$

*With image formation.* As it is not possible to obtain uniform irradiance, the sum of the individual radiant intensities per unit area can only be calculated by measuring the total radiation flux  $\Phi$  by means of the aperture angle  $\omega$ . Using equations (6) and (7) we find:

$$\begin{aligned}\Phi &= I\omega = \{I(\lambda_1) + I(\lambda_2) + \dots + I(\lambda_n)\}f_s/d^2 \\ &= \{L(\lambda_1) + L(\lambda_2) + \dots + L(\lambda_n)\}h\alpha f_s/d^2\end{aligned}\quad (47a)$$

where  $d$  = distance between exit slit and image-forming means.

Whether or not an optical image is used, it is always necessary to check how far the irradiance is identical at the position of the detector for the entire receiving surface, particularly in respect of the spectral composition. Such irregularities can contribute to measurement errors, especially when photoelectric detectors are used, the spectral sensitivity of which is never constant over the entire surface.

When the area of the receiving surface is known, the corresponding radiation flux can be derived from the irradiance. In the case of a receiver large enough to encompass the entire pencil of rays emerging from the exit slit, the total emerging radiation flux is available. It is, however, often preferable to make the receiving surface a little smaller than the diameter of the pencil of rays, in order to obtain a completely uniform irradiation of the receiving surface. In such a case the irradiance is arrived at. This gives the radiant intensity per unit area using equation (47), provided the other factors are known.

## 2. Measurement with a detector of known spectral sensitivity

With a detector of known spectral sensitivity following the exit slit of a monochromator we can determine the irradiance for the wavelength region transmitted by the monochromator. Depending on the imaging conditions, we can calculate the corresponding radiant intensity per unit area in the exit slit by means of equations (46) and (47). The total losses in transmission are taken into account by the transmission factor of the monochromator.

It is no simple matter to arrive at the absolute values of the radiant intensity per unit area in this way, because of the difficulty in determining an absolute value for the transmission factor  $\tau(\lambda)$  with sufficient precision. But measurement of the parameters given in equations (46) and (47) is also complicated.

We are therefore content to determine the relative values for radiant intensity per unit area in the manner described, because we only need a relative value for  $\tau(\lambda)$ , namely  $\tau(\lambda)_r$ , while the measurement of the aperture can be omitted. Furthermore, only relative values are needed in this case to express the spectral sensitivity of the detector  $s(\lambda)_r$ .

*Example No. 1.* Relative spectral radiation distribution of a line radiator.

For the spectral transmission factor of the monochromator (including any optical imaging device and spectral sensitivity of the detector) relative

values  $\tau(\lambda)_r$  and  $s(\lambda)_r$  are known, while the ray-geometry, as well as slit widths and lengths are taken into account by a factor independent of wavelength  $P_1$ . The reading of the detector is  $I(\lambda)$  at wavelength  $\lambda$  and  $I(\lambda_0)$  for reference wavelength  $\lambda_0$ . Equations (42), (46) and (47) give:

$$I(\lambda) = L(\lambda)\tau(\lambda)s(\lambda)P_1; \quad I(\lambda_0) = L(\lambda_0)\tau(\lambda_0)s(\lambda_0)P_1$$

$$L(\lambda)_r = \frac{L(\lambda)}{L(\lambda_0)} = \frac{I(\lambda)}{I(\lambda_0)} \cdot \frac{\tau(\lambda_0)s(\lambda_0)}{\tau(\lambda)s(\lambda)} = \frac{I(\lambda)}{I(\lambda_0)} \cdot \frac{1}{\tau(\lambda)_r s(\lambda)_r} \quad (48)$$

*Example No. 2.* Relative spectral radiation distribution of a continuous radiator.

Apart from values  $\tau(\lambda)_r$  and  $s(\lambda)_r$ , relative values for the dispersion  $D(\lambda)_r$  are known. The reading of the detector at wavelength  $\lambda$  is again  $I(\lambda)$  and at wavelength  $\lambda_0$  correspondingly  $I(\lambda_0)$ . The ray-geometry including slit widths and lengths is taken into account by a factor  $P_2$  independent of wavelength. Equations (45), (46) and (47) give:

$$I(\lambda) = L_\lambda \tau(\lambda)s(\lambda)P_2/D(\lambda); \quad I(\lambda_0) = L_\lambda(\lambda_0)\tau(\lambda_0)s(\lambda_0)P_2/D(\lambda_0)$$

$$(L_\lambda)_r = L_\lambda/L_\lambda(\lambda_0) = \{I(\lambda)/I(\lambda_0)\} \{\tau(\lambda_0)s(\lambda_0)D(\lambda)/\tau(\lambda)s(\lambda)D(\lambda_0)\}$$

$$= \{I(\lambda)/I(\lambda_0)\} \{D(\lambda)_r/\tau(\lambda)_r s(\lambda)_r\} \quad (49)$$

The absolute values can be calculated from the relative values in the usual manner, provided at least one absolute value is known (see II, 3, equation (13)).

Because of the difficulty mentioned, such a determination of absolute values will hardly be made for constants  $P_1$  and  $P_2$ , neither for absolute values  $\tau(\lambda)$ ,  $s(\lambda)$  and  $D(\lambda)$ . It is far easier to carry out a measurement with a radiator of known spectral emission (see 3) or by using filters (see Chapter XII).

### 3. Measurement with a radiator of known spectral emission

When making a measurement with a radiator of known spectral emission, all the difficulties mentioned in (2) cease to exist. The only necessary precaution is that the measurement conditions are identical for both radiators in every respect. This is particularly important with regard to the aperture of the collimating lens. A further condition is that the two radiators are of identical dimensions and have uniform radiance over their radiant surfaces.

Identical dimensions of the operative surfaces are simply obtained by imaging identical sections of the radiant surfaces. But when the radiance is not uniform over the entire surface, or when radiators of different dimensions have to be compared, only the use of irradiation by an auxiliary surface as described in Chapter X, 6, *d*, can solve the difficulty. As explained there, the radiant intensities can be compared in this way.

Depending on whether absolute values or only relative values are known for the comparison radiators, absolute or relative values will result for the



radiator under examination. When pure line radiators or pure continuous radiators are compared, one does not have to know the dispersion or spectral slit widths. These values need be known only when comparing a line radiator with a continuous radiator, and, in particular, when a radiator emits a mixed line and continuous spectrum.

The two radiators are characterized in the following examples by the subscripts 1 and 2.

*Example No. 1.* Comparison of two line radiators.

Both radiators are imaged on the entrance slit under identical conditions and both radiant surfaces are of sufficient dimensions to illuminate the slit fully. The receiver reading of one radiator is  $I_1$  and that of the other is  $I_2$ . The detector reading depends on the irradiance at the detector, which is determined by means of equations (46) and (47), by the radiant intensity per unit area  $L(\lambda)$  in the exit slit, and according to Chapter XI, 1 by the radiant intensity per unit area of the radiator. The radiant intensities per unit area are therefore directly compared:

$$L_1(\lambda)/L_2(\lambda) = I_1/I_2; \quad L_1(\lambda) = L_2(\lambda)I_1/I_2 \quad (50)$$

*Example No. 2.* Comparison of two continuous radiators.

Here too, both radiator surfaces are imaged on the entrance slit under exactly the same conditions and the radiator surfaces must be large enough to illuminate the full slit area.

As the effective wavelength interval, defined by slit widths  $a$  and  $b$ , is identical in both cases, the same relationship is obtained as in the case of line radiators, but here for the spectral concentration of radiant intensity per unit area.

Radiator 1 gives an indication  $I_1$ ; radiator 2 gives an indication  $I_2$ , so that:

$$(L_\lambda)_1/(L_\lambda)_2 = I_1/I_2; \quad (L_\lambda)_1 = (L_\lambda)_2 I_1/I_2 \quad (51)$$

*Example No. 3.* Comparison of a line radiator with a continuous radiator.

The line radiator with radiant intensity per unit area  $L(\lambda)$  produces radiant intensity  $I_1(\lambda) = L(\lambda)ha(a \leq b)$  in the exit slit (equation (42)). The continuous radiator, on the other hand, with spectral concentration of intensity per unit area  $L_\lambda$  has a radiant intensity  $I_2(\lambda) = L_\lambda hab/D$  (equation (44)). Giving the values  $I_1$  and  $I_2$  to the detector readings, we obtain:

$$I_1(\lambda)/I_2(\lambda) = L(\lambda)/(L_\lambda b/D) = I_1/I_2; \quad L(\lambda) = L_\lambda(I_1/I_2)(b/D) = L_\lambda \beta I_1/I_2 \quad (52)$$

The equation can, of course, also be solved for  $L_\lambda$ . A factor entering into the comparison calculation is the width of the outlet slit expressed in wavelength units  $\beta = b/D$ , which will, in general, have different values in different spectral regions, because  $D$  depends on the wavelength. When  $a > b$ , then  $I_1(\lambda) = L(\lambda)hb$  and in equation (52)  $\beta$  is substituted by  $a/D = \alpha$ .

When the line radiator itself has a continuous spectrum superimposed on it, the readings for this continuous spectrum are made at wavelengths as closely as possible to the lines and readings are interpolated to the positions of the lines. The reading for the continuous spectrum so obtained at the place of a line is deducted from the reading at the same place for line plus continuous spectrum. In this way the proper reading for the line only is obtained.<sup>52,72</sup>

There also exists a slightly more complicated method for separating the lines from the continuous spectrum, which is capable of giving more precise results. The separation is obtained by varying the width of the exit slit.<sup>146</sup>

## **XII. MEASUREMENT OF SPECTRAL EMISSION OF RADIATORS BY MEANS OF FILTERS**

### *1. Introduction*

#### *(a) Method and transmission factor*

The isolation of a small wavelength band, as is usual for spectral measurement, is in many respects easier to achieve with a filter than with a monochromator. All that is necessary is to insert the filter at a suitable place in the path of the rays, which do not suffer any change if certain precautions are observed. In this way it is possible to obtain larger fields of radiation providing uniform irradiation than with a monochromator. Another advantage is that for the same isolated wavelength range, the values of the intensity are mostly higher since losses are generally lower with filters because of their larger transmission factors. The main advantage, however, is that with filters, the absolute values of spectral transmission factors can be established more easily.

According to equation (15) the transmission factor is the ratio of transmitted to incident radiation flux. When the measurement is effected at the same point, this is simply the ratio of the irradiation with filter to that without filter, always provided that only the amount of radiation is changed and not the direction of radiation. Were the filter, for instance, in the shape of a lens, an increase in radiation may result at the point of measurement because of the converging action of the lens, instead of a reduction in radiation due to absorption and scatter. The transmission factor would then be greater than 1 with a lens-shaped filter.

Similar effects can appear as a result of using wedge filters, or those with bubbles and streaks, even when the filter surfaces are flat. An important precaution is to use only high-quality plane-parallel filters, so that no changes occur in the direction of the path of rays. Of course, there will always be a slight change in the path of rays due to refraction, but this can be neglected in most cases with thin filters. Their effects are represented in the transmission factor and they do not have to be considered separately.

As the transmission factor depends on the effective lengths of the paths of rays through the filter, they should be made of uniform length over the entire diameter of the pencil of rays. The latter should therefore be as parallel as possible. This is of prime importance with interference filters (see V, 4). When absolute values of radiation flux are measured, no image formation method will be used and the radiator should then be placed at a certain minimum distance to obtain an approximation to a pencil of parallel rays.

The filter material should be of a homogeneous nature over the entire effective surface; otherwise it would be impossible to attribute a unique transmission factor to it.

*As the transmission factor of a filter can depend in many ways on the manner of insertion in the path of rays, the transmission factor should be established under exactly the same conditions as those in which the filter is to be used in measurement.*

Monochromatic radiation is required for measuring the spectral transmission factor of a filter. This can be achieved by using either other filters or a monochromator.

It is difficult to indicate general rules for the best position of the filter in the path of rays, but it is always important to prevent heating of the filter by the often intense primary radiation, because the transmission factor of many filters depends on the temperature. Perhaps the best position is as close as possible to the detector, which fortunately corresponds with other desiderata.

Basically, the same measurements can be made with filters as with monochromators; only slight changes in the appropriate relations are needed. A monochromator can be conceived as a filter, where the curve of spectral transmission, determined by the slit width, always has the shape of a trapezium or triangle.

We should mention that the most suitable method, when making a measurement without image formation in the filtered radiation field, is to take the irradiance as the starting point. This ensures perfect measurement of radiators with a large radiant surface, for which it is difficult or impossible to determine the radiant intensity (and therefore radiant intensity per unit area) at short distances. When strong fluctuations in the radiance occur on the radiant surface (as is often the case) the radiator is best characterized by its irradiance. If the distances are sufficiently long, the other radiation values can be calculated from the irradiance, as described in Chapter VI, 3.

On the other hand, it is practically impossible—in the case of monochromator measurement—to calculate the irradiance in the radiation field of the radiator, or other values, from the irradiance at the detector. This is particularly important when the radiance of the radiant surface has various values and only part of the radiant surface can be imaged on the slit of the monochromator (see Chapter XI).

#### (b) Line radiators

When only a single line lies within the transmission range of a filter, the value of the irradiance  $E_F$  following the filter, will be independent of the spectral width:

$$E_F = E(\lambda)\tau(\lambda) \quad (53)$$

where  $E(\lambda)$  = irradiance without filter.

The corresponding detector reading  $I$ , when  $s(\lambda)$  represents the spectral sensitivity of the detector for the wavelength in question, will be:

$$I = E_F s(\lambda) = E(\lambda) \tau(\lambda) s(\lambda) \quad (54)$$

(c) Continuous radiators

In the absence of special assumptions, the irradiance  $E_F$  after the filter, the transmission range of which is from  $\lambda_1$  to  $\lambda_2$ , will be:

$$E_F = \int_{\lambda_1}^{\lambda_2} E_\lambda \tau(\lambda) d\lambda \quad (55)$$

where  $E_\lambda$  = spectral irradiance without filter.

The corresponding detector reading  $I$  will be:

$$I = \int_{\lambda_1}^{\lambda_2} E_\lambda \tau(\lambda) s \lambda d\lambda \quad (56)$$

where  $s(\lambda)$  = spectral sensitivity of detector.

## 2. Measurement with a detector of known spectral sensitivity

Let us assume that the detector with a spectral sensitivity  $s(\lambda)$  is placed in the proper position in the radiation field of the radiator and that the filter with a spectral transmission factor  $\tau(\lambda)$  is inserted at the most suitable place in the path of rays (without optical image formation).

When the transmitted wavelength range is sufficiently narrow, the corresponding values of the irradiance can be calculated. When the transmitted wavelength range is longer, the relative spectral radiation distribution must be already known.

Both selective and non-selective detectors can be used, but the latter are to be preferred. As radiation fields of larger dimensions are available, the largest possible receiving area is selected, as for instance with a thermopile or bolometer.

### *Example No. 1. Measurement of a line radiator.*

The transmission range of the filter includes only a single line, for which the value  $\tau(\lambda)$  is known. Representing the irradiance for this line without filter at the position of the detector by  $E(\lambda)$  and the reading of the measuring instrument by  $I$ , we find by using equation (54):

$$E(\lambda) = I / \tau(\lambda) s(\lambda) \quad (57)$$

### *Example No. 2. Measurement of a continuous radiator with a filter of narrow spectral transmission.*

Let us assume that the transmission range of the filter from  $\lambda_1$  to  $\lambda_2$  is so small that a single value for the spectral irradiance  $E_\lambda$  and for the spectral

sensitivity  $s(\lambda)$  can be taken. Representing the spectral irradiance without filter at the position of the receiver by  $E_\lambda$  and the reading of the measuring instrument by  $I$ , equation (56) gives us:

$$I = E_\lambda s(\lambda) \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda; \quad E_\lambda = I / s(\lambda) \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda \quad (58)$$

*Example No. 3.* Measurement of a continuous radiator with a filter of wider transmission.

Measurement is only possible when the relative spectral radiation distribution  $(E_\lambda)_r$  is already known. According to equation (56) and assuming that values  $\tau(\lambda)$  and  $s(\lambda)$  are known, equation (12a) having taught us that  $E_\lambda = C(E_\lambda)_r$ :

$$I = C \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r \tau(\lambda) s(\lambda) d\lambda; \quad C = I / \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r \tau(\lambda) d\lambda \quad (59)$$

The value of  $C$  is found by calculating the integral. The spectral irradiance required is then:

$$E_\lambda = (E_\lambda)_r I / \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r \tau(\lambda) s(\lambda) d\lambda \quad (59a)$$

### 3. Measurement with a radiator of known spectral emission

The known radiator is characterized by its spectral irradiance at the position of the detector. The radiator to be measured can be arranged at any desired distance from the detector, although it is easier to maintain equal distances for both radiators as we then have entirely identical paths of rays. This is always a good plan as it prevents the introduction of any additional measurement errors.

In this case, we are merely comparing two radiators. Therefore we do not need to know the degree of spectral transmission  $\tau(\lambda)$  nor the spectral sensitivity of the receiver  $s(\lambda)$ , provided the width of the transmission band of the filter is very small. Should this not be the case, it is necessary to know the above mentioned values as well as the relative spectral radiation distribution of the radiator to be examined.

The two radiators are given the subscripts 1 and 2 in the following examples.

*Example No. 1.* Comparison of two line radiators with a filter of narrow spectral transmission range.

The transmission band of the filter is to be so small, indeed, that only a single line, common to both radiators, is transmitted. The detector reading of the first radiator is given the value  $I_1$ , that of the second radiator  $I_2$ . Then, considering equation (54), we find:

$$E(\lambda)_1 \tau(\lambda) s(\lambda) / E(\lambda)_2 \tau(\lambda) s(\lambda) = I_1 / I_2; \quad E(\lambda)_1 = (I_1 / I_2) E(\lambda)_2 \quad (60)$$

*Example No. 2.* Comparison of two continuous radiators with a filter of narrow spectral transmission range.

In this case, one can assume uniform values for the spectral irradiance  $E_\lambda$  and the spectral sensitivity of the detector  $s(\lambda)$  in the transmission range of the filter. Once more calling the detector readings  $I_1$  and  $I_2$ , equation (56) gives us:

$$(E_\lambda)_1 s(\lambda) \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda / (E_\lambda)_2 s(\lambda) \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda = I_1/I_2; \quad (E_\lambda)_1 = (I_1/I_2)(E_\lambda)_2 \quad (61)$$

*Example No. 3.* Comparison of two continuous radiators with a filter of wider transmission band.

Here we need not only to know the spectral radiation distribution  $(E_\lambda)_1$  of the comparison radiator, but also the relative radiation distribution of the radiator under examination  $(E_\lambda)_{r,2}$ . Equation (12a) gives:

$$(E_\lambda)_1 = C_1(E_\lambda)_{r,1}; \quad (E_\lambda)_2 = C_2(E_\lambda)_{r,2}$$

where  $(E_\lambda)_{r,1}$  is the relative spectral radiation distribution of the comparison radiator, which is determined by  $(E_\lambda)_1$ .

When the detector readings are once more  $I_1$  and  $I_2$ , according to equation (56) we find:

$$C_1 \int_{\lambda_1}^{\lambda_2} (E_\lambda)_{r,1} \tau(\lambda) s(\lambda) d\lambda / C_2 \int_{\lambda_1}^{\lambda_2} (E_\lambda)_{r,2} \tau(\lambda) s(\lambda) d\lambda = C_1 K / C_2 = I_1/I_2 \quad (62)$$

The constant  $K$  is the quotient of the two integrals.

As  $(E_\lambda)_1$  and  $(E_\lambda)_{r,1}$ , as well as  $C_1$  and  $(E_\lambda)_{r,2}$  are known, it is possible to calculate  $C_2$  and  $(E_\lambda)_2$ :

$$(E_\lambda)_2 = C_2(E_\lambda)_{r,2} = (E_\lambda)_{r,2}(I_2/I_1)C_1K = \{(E_\lambda)_{r,2}/(E_\lambda)_{r,1}\}(I_2/I_1)K(E_\lambda)_1 \quad (63)$$

When the two relative radiation distributions have the same value,  $K$  will be 1, and we find the simple equation:

$$(E_\lambda)_2 = (I_2/I_1)(E_\lambda)_1 \quad (63a)$$

*Example No. 4.* Comparison of a line radiator with a continuous radiator by means of a filter with narrow transmission band.

The filter transmits only one line  $E(\lambda)_1$  and the continuous spectrum can be characterized in the narrow transmission band of the filter by a single value  $(E_\lambda)_2$ . Let the receiver indications be  $I_1$  and  $I_2$ , then we find by using equations (54) and (56):

$$E(\lambda)_1 \tau(\lambda) s(\lambda) / (E_\lambda)_2 s(\lambda) \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda = I_1/I_2; \quad E(\lambda)_1 = (I_1/I_2)(E_\lambda)_2 \int_{\lambda_1}^{\lambda_2} \tau(\lambda) d\lambda / \tau(\lambda) \quad (64)$$

*Example No. 5.* Comparison of a line radiator with a continuous radiator by means of a filter of wider transmission band.

This filter will encompass a larger section of the continuous spectrum  $(E_\lambda)_2$ , but only one line of the line spectrum  $E(\lambda)_1$ . The relative spectral radiation distribution of the continuous spectrum  $(E_\lambda)_{r,2}$  must be known. When the detector readings are  $I_1$  and  $I_2$ , equations (54) and (56) give, by consideration of equation (12a):

$$E(\lambda)_1 \tau(\lambda) s(\lambda) / C_2 \int_{\lambda_1}^{\lambda_2} (E_\lambda)_{r,2} \tau(\lambda) s(\lambda) d\lambda = I_1 / I_2 \quad (65)$$

As  $\tau(\lambda)$  and  $s(\lambda)$  can be assumed to be known, the integral can be evaluated and we arrive at the simplified expression:

$$E(\lambda)_1 K^* / C_2 = I_1 / I_2; \quad E(\lambda)_1 = (I_1 / I_2) C_2 / K^*$$

where

$$K^* = \tau(\lambda) s(\lambda) / \int_{\lambda_1}^{\lambda_2} (E_\lambda)_{r,2} \tau(\lambda) s(\lambda) d\lambda \quad (66)$$

When the irradiance  $E(\lambda)_1$  for the line is known,  $C_2$  and thereby the absolute spectral radiation distribution of the continuous spectrum can be calculated, and vice versa.



### XIII. MEASUREMENT OF TOTAL RADIATION

#### 1. *Introduction*

When we speak of total radiation, we usually mean the total radiation emitted by a continuous radiator, particularly a thermal radiator, although we may also include the radiation from a line radiator. In the latter case, we mean by total radiation simply the total of all radiation emitted by a radiator. When the spectral radiation distribution is to be calculated, it is useful to give each spectral line a mean spectral emission and a mean spectral width (see Chapter II, 4).

Measurement of total radiation is done without optical image formation, if such imaging can be avoided, in order to avoid losses in the lenses and mirrors forming the image. As the available flux is always much greater than in the case of spectral measurements, there is hardly any need for an optical system.

The radiation detector is arranged at the appropriate place in the radiation field and there the irradiance is measured for the desired position of the receiving surface. If it is possible to specify a single emission direction, the receiving surface will normally be placed perpendicular to that direction, unless specific mention is made of a different arrangement (in equation (9a)  $\cos \varepsilon_2 = 1$ ).

The determination of such a single emission direction is always possible when a certain minimum distance between radiator and detector is exceeded. Equation (9a) then permits the calculation of the radiant intensity from the irradiance.

For the measurement of total radiation, one needs detector sensitivity over a large spectral range. The idea of "overall sensitivity" was introduced in equation (38). In specific cases, there are simplified versions of this equation (38a, b and c).

#### 2. *Measurement with a detector of known spectral sensitivity*

We have already mentioned in Chapter X, 4a that a selective detector can only be used for the measurement of total radiation when in addition the relative values of the spectral emission  $(E_\lambda)_r$  of the radiation under examination are known. With the emission of the radiator to be examined ranging between  $\lambda_1$  and  $\lambda_2$ , equation (38a) gives us:

$$s(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r s(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} (E_\lambda)_r d\lambda = l/E \quad (67)$$

where  $s(\lambda)$  = spectral sensitivity of the selective detector;  
 $l$  = the detector reading;  
 $E$  = irradiance of the total radiation between  $\lambda_1$  and  $\lambda_2$ .

As it is possible to evaluate the integrals,  $s(\lambda_1, \lambda_2)$  can be calculated. Equation (38) gives:

$$E = l/s(\lambda_1, \lambda_2) \quad (68)$$

As for a non-selective detector  $s(\lambda) = s$ , according to equation (38c):  $s(\lambda_1, \lambda_2) = s$ , independently of  $E$ , the equation simplifies to

$$E = l/s \quad (68a)$$

*The relative spectral emission of the radiator under examination is no longer needed for the calculation and therefore does not need to be known.*

The measurement of total radiation with a non-selective detector is therefore relatively simple. If the relative spectral emission of the radiator is not known, a non-selective detector is always necessary.

### 3. Measurement with a radiator of known spectral emission

We have seen in Chapter X, 4b that measurement of total radiation with a selective detector is only possible in this case, when apart from the relative spectral emission of the radiator to be measured  $(E_\lambda)_{r,x}$ , the relative spectral sensitivity of the receiver  $s(\lambda)_r$  is also known.

First, we have to take into consideration that according to equations (12a) and (37a) the following connection exists between relative and absolute values:

$$(E_\lambda)_x = E_\lambda(\lambda_0)_x \cdot (E_\lambda)_{r,x}; \quad s(\lambda) = s(\lambda_0) \cdot s(\lambda)_r$$

The measurement which is a comparison of two radiators, is best effected in two steps.

(a) Measurement with the known radiator of the spectral emission  $E_\lambda$  between  $\lambda_1$  and  $\lambda_2$  will give an indication  $l$ . Its value is according to equation (37):

$$l = s(\lambda_0) \int_{\lambda_1}^{\lambda_2} E_\lambda s(\lambda)_r d\lambda; \quad s(\lambda_0) = l / \int_{\lambda_1}^{\lambda_2} E_\lambda s(\lambda)_r d\lambda \quad (69)$$

As the integral can be evaluated,  $s(\lambda_0)$  and therefore also  $s(\lambda)$  are known.

(b) Measurement with the radiator under examination of the relative spectral emission  $(E_\lambda)_{r,x}$  between  $\lambda_3$  and  $\lambda_4$  is done in the same way as described under (2) because the spectral sensitivity of the detector has already been

obtained by measurement (a). Equation (38a) permits the calculation of the overall sensitivity  $s(\lambda_3, \lambda_4)$  for the radiator to be measured:

$$s(\lambda_3, \lambda_4) = \int_{\lambda_3}^{\lambda_4} (E_\lambda)_{r,x} s(\lambda) d\lambda / \int_{\lambda_3}^{\lambda_4} (E_\lambda)_{r,x} d\lambda \quad (70)$$

When  $l_x$  is the detector reading obtained with the radiator to be measured, equation (38) gives the total radiation  $E_x$ :

$$E_x = l_x / s(\lambda_3, \lambda_4) = (l_x / l) \int_{\lambda_3}^{\lambda_4} (E_\lambda)_{r,x} d\lambda \int_{\lambda_1}^{\lambda_2} E_\lambda s(\lambda)_r d\lambda / \int_{\lambda_3}^{\lambda_4} (E_\lambda)_{r,x} s(\lambda)_r d\lambda \quad (71)$$

This expression is considerably simplified when a non-selective detector is used, because in this case  $s(\lambda) = s$  and  $s(\lambda)_r = 1$ . Hence:

$$E_x = (l_x / l) \int_{\lambda_3}^{\lambda_4} E_\lambda d\lambda = (l_x / l) E \quad (71a)$$

where  $E$  = total radiation of the known radiator.

*It is not necessary to know the relative spectral emission of the radiator to be measured as it does not appear in the equation.*

The equation does already contain the sensitivity of the non-selective detector namely  $s = l/E$ . This value is therefore determined at the same time.

In this case, too, the use of a non-selective detector considerably facilitates the measurement and its use is equally indispensable when the relative spectral emission of the radiator to be measured is not known.

*It will be clear that in practice non-selective detectors are used for these purposes exclusively.*

Nevertheless, it is useful to consider the corrections which are necessary in the case of selective detectors. For on one hand it may happen that no non-selective receiver is available for a specific measurement in the desired spectral range and on the other hand it is possible to make corrections when small deviations from non-selectivity have been ascertained.

As there are no losses between radiator and detector (apart from air absorption and scatter), the arrangements for the measurement with detectors of known sensitivity and radiators of known emission are practically the same. In the second case, the value for the sensitivity of the detector is also obtained.

When it is necessary to consider air losses, as can be possible in the infra-red band because of the presence of water vapour and carbon dioxide in the surrounding air, it is better to carry out the measurement by comparing two radiators. These should however have relative spectral emissions as near the same as possible.

When the relative spectral radiation distribution is identical for both radiators, any detector can be used in any arbitrarily selected spectral region. Equation (71) is then simplified as follows:

$$E_x = (I_x/I)E \quad (71a)$$

It is true, however, that this condition is hardly ever fully met in practice.

#### 4. *Choice of detector and comparison radiator*

Measurement with a detector which permits comparison with another form of energy (Chapter X, 2), as well as measurement by comparison with a black body radiator, are only possible in a specially equipped laboratory. A bolometer or a thermopile will be used, the sensitivity having been measured beforehand. When the detector sensitivity is not known, a filament lamp is used as "standard," the total radiation having been measured beforehand. A measurement by comparison is then carried out. Gas discharge lamps have not been used so far for these purposes.

The required determination of the detector sensitivity or filament lamp emission is preferably done by a national laboratory (in Great Britain the National Physical Laboratory), which is specially equipped for calibrations of this kind.

As it is advantageous to use as large a portion as possible of the radiation field, the receiving surface is made as large as possible. Apart from the practical limits imposed by the detector design, care should be taken to ensure that the irradiance is uniform over the entire receiving surface. This means that the distance between radiator and detector must be large and that the receiving surface must be small compared with the dimensions of the radiator.

Commercially available thermopiles and bolometers have a receiving surface of the order of 1 to 10 cm<sup>2</sup>. A protective window is often incorporated, which should only be used if its transmission in the spectral region concerned does not show any selectivity. As this is only rarely the case, it is recommended that a protective window should not be used for measurement of total radiation. For the same reason, vacuum detectors are hardly ever used in this case.

When a comparison radiator is used for the measurement of total radiation, it is always an advantage if its relative spectral radiation distribution corresponds as closely as possible with that of the radiator under examination. Any selectivity of detector sensitivity is then of less importance. The ideal case of two radiators having identical relative spectral radiation distribution has already been discussed; in the case of a selective detector it led to the simple relationship of equation (71a).

On the other hand, accommodation to such conditions is often not possible, even when both radiators are filament lamps. The reason for this is that the

standard lamp used for comparison measurement has to be run at a certain prescribed current and this determines its spectral radiation distribution.

When a number of such measurements have to be carried out at frequent intervals, it is recommended that a "sub-standard" be obtained which has a spectral radiation distribution approximating to the radiator under examination. Its total radiation will have to be carefully determined and will be used as a basis for further measurements. In this way, a series of measurements of a large number of radiators can be carried out at less cost and in much shorter time.

### *5. Measurement technique*

The arrangement is the same for measurements of both detectors of known sensitivity and radiators of known emission.

The basic set-up for radiation measurement, including total radiation, consists of a radiator, a flap-shutter to exclude radiation and a detector.

With the flap-shutter in the closed position, the detector receives only the radiation from the shutter and its surroundings. With the shutter in the open position, the detector will receive the radiation emitted by the radiator to be measured and its surroundings (also called "background"). In addition, the detector also emits radiation to the shutter and its surroundings, or to the radiator and the background.

As the temperatures of detector, shutter, surroundings and background do not differ very much and only emit thermal radiation in normal cases, only very long-wave infra-red radiation can be effective (see equations (24) and (25)). If the detector, e.g. a barrier layer photovoltaic cell, does not react to infra-red, this radiation can be ignored. But in the case of measurement of total radiation, particularly in the infra-red region, the additional radiation from the different parts of the apparatus must be taken into account.

First of all it is necessary to render the radiation of the surroundings—which may also include indirectly reflected radiation from other sources—as harmless as possible by using a number of diaphragms which should be as black as possible.

The purpose of these diaphragms is to limit the solid angle of the incident radiation—to which the detector reacts—in a suitable way. How these diaphragms are positioned depends on the particular experimental conditions (see Fig. 69).

If it is required to change the position of the detector often, as may be the case for changes in distance, a set of diaphragms is recommended which form a physical unit with the detector. The dimensions of such a set obviously are restricted (see Fig. 70).

Two contradictory conditions exist for the position of the shutter. If it is too close to the radiator, radiation can cause objectionable heating. If the shutter is positioned close to the detector, the danger exists that radiation from the surroundings is included in the measurement. The best possible position

should therefore be ascertained by experiment, depending on the special conditions of each case.

While the side of the flap facing the receiver should be black, the other side should have a highly reflecting surface, in order to avoid heating of the flap as much as possible.

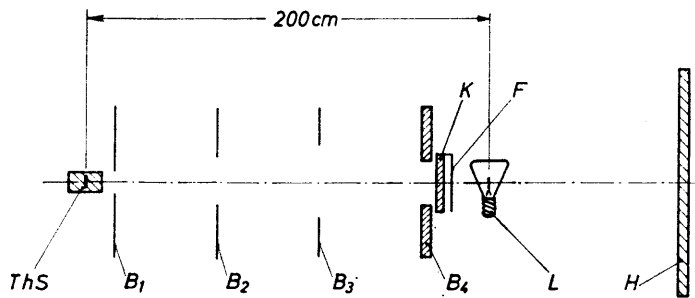


Fig. 69 Measurement arrangement for total radiation. L: radiator; ThS: thermopile; B<sub>1</sub>, B<sub>2</sub>, B<sub>3</sub>, B<sub>4</sub>: diaphragms; H: background; K: flap-shutter with reflecting surface F; ThS, B<sub>4</sub>, K, H are maintained at a constant temperature, approximately room temperature, if necessary by a water jacket.

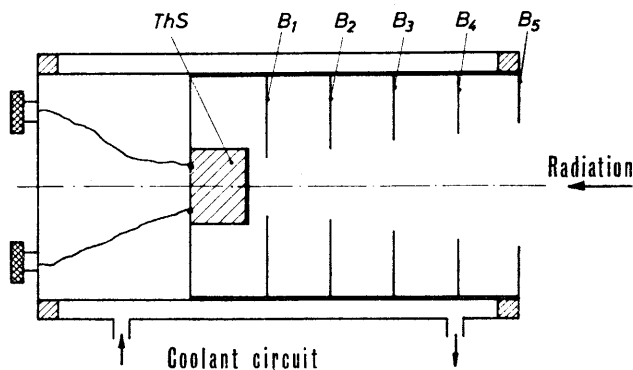


Fig. 70 Thermopile with attached set of diaphragms (in water jacket). ThS: thermopile; B<sub>1</sub>, . . . B<sub>5</sub>: diaphragms.

With regard to the background, we should note that both its thermal radiation and possibly indirectly reflected radiation which may emanate from the radiator itself, are included. The best method, therefore, is to employ a highly absorbing (i.e. black) wall which is placed at such a distance from the radiator that it is not perceptibly heated by its radiation.

Finally we should consider to what extent the emission of the radiator to be examined is influenced by the temperature of the surroundings.

This is not serious in the case of thermo-radiators of high temperature, because the quantity  $T_0^4$  in the expression  $T^4 - T_0^4$  (which determines the total emission) is very much smaller than  $T^4$  (see equation (24b)). Gas discharge radiators, e.g. UV standards, are mostly operated in a housing, which is the

determining factor for the radiator temperature. The usual fluctuations in room temperature do not count in this case.

We can conclude from the above that, for measurement of total radiation, the best method is to ensure a completely uniform temperature of all the parts of the apparatus which may have an influence on the measurement, in particular the detector, the flap and the background. The easiest way to accomplish this is to use a water jacket which keeps all these parts at room temperature. A thermostat is not necessary, provided the emitted radiation flux is not too high.

Once this constant temperature has been achieved, opening of the flap after removal of the radiator will not cause any variation in the detector reading. This is due to the fact that the background (which is of uniform temperature) replaces the flap, so that no change in radiation conditions takes place. Strictly speaking it is not even required that the detector has the same temperature as background and flap. However, in order to prevent any objectionable heating, it is always better to include the detector in the cooling system.

If there is any difference of temperature, especially between flap and background, the following possibilities arise:

If the flap is cooler than the background, the radiator is removed and that part of the background radiation is measured which exceeds the radiation of the flap. The reading will move in the same direction as that obtained when measuring the radiator.

If the flap is warmer than the background, the additional radiation will disappear when the flap is opened. The reading will now move in the opposite direction from that obtained when measuring the radiator.

These relationships can be represented as follows:

Flap in relation to background	Reading without radiator (background)	Reading with radiator (radiator and background)	Radiator only
cooler	$+u$	$+v = u + x$	$x = v - u$
warmer	$-u$	$+v = -u + x$	$x = v + u$

Strictly speaking, the background temperature should be measured when making these corrections for a radiator which is present in a cut-off position in the path of the rays. The long-wave infra-red of the background radiation may be absorbed by the glass envelope of a filament lamp. For the greatest precision, this absorption should be measured at the working temperature of the lamp. But this measurement will be dependent on the radiation of the lamp which is superimposed. This introduces complications. As the correction is mostly small, too much importance should not be attributed to this problem. On the other hand it is so much more convenient not to have these problems in the first place by arranging for a uniform temperature of the entire apparatus.

## XIV. MEASUREMENT OF DETECTOR SENSITIVITY

### 1. Introduction

As we have seen in Chapter VII, 3 and 4, we distinguish between absolute spectral sensitivity, relative spectral sensitivity, overall sensitivity and—in the absence of spectral dependency—simply “sensitivity.” In the last case, the spectral sensitivity is the same throughout the spectrum and the relative spectral sensitivity = 1.

Before stating the sensitivity of a detector, it is necessary to check if the reading is proportional to the irradiance (Chapter VII, 1). It is also important to know if equal irradiance at different, same-sized parts of the receiving surfaces, give equal readings. Finally, we should also know the extent to which, by simultaneous irradiation of different parts of the receiving surface, the corresponding detector reading is the same as the sum of the previously measured readings. It will be necessary to check that no spectral variations exist in this respect.

As discussed in Chapter X, 5, measurement of detector sensitivity can be carried out either by means of a detector of known spectral sensitivity or by means of a radiator of known spectral emission.

### 2. Measurement of spectral sensitivity

The determination of spectral sensitivity, as defined in equation (37), assumes monochromatic radiation, obtainable by means of a monochromator or filter, as already described.

Is the measurement made by comparison with a detector of known spectral sensitivity, all that is necessary is to place the two detectors one after the other at the same position in the monochromatic field of radiation and to measure the corresponding receiver readings  $I_1$  and  $I_2$ . When the spectral sensitivities of the two receivers are  $s_1(\lambda)$  and  $s_2(\lambda)$  respectively and the monochromatic irradiance  $E(\lambda)$ , then:

$$E(\lambda) = I_1/s_1(\lambda) = I_2/s_2(\lambda); \quad s_1(\lambda) = (I_1/I_2)s_2(\lambda) \quad (72)$$

When two detectors with receiving surfaces greatly different in size, must be compared, e.g. a photovoltaic cell with a thermopile, it may be necessary to place the two detectors at different positions of the radiation field.

In this case it is true that the relative spectral radiation distribution is the same for both detectors, but the absolute values of the irradiance will be different by the wavelength-independent factor  $q$ . Calling the spectral sensitivities  $s_1(\lambda)$  and  $s_2(\lambda)$  and the corresponding detector readings  $I_1$  and  $I_2$ , we find:

$$qE(\lambda) = I_1/s_1(\lambda); \quad E(\lambda) = I_2/s_2(\lambda); \quad s_1(\lambda) = (I_1/qI_2)s_2(\lambda) \quad (72a)$$



When the relative values are expressed in the manner of equation (37a), the factor  $q$  cancels out, so that the relative spectral sensitivity can be obtained by this method.

When measuring with a radiator of known spectral emission, it is necessary to know the degree of spectral transmission  $\tau(\lambda)$  of the equipment used (monochromator or filter) and sometimes also the ray-geometry, in order to be able to determine the spectral concentration of irradiance  $E(\lambda)$ . This problem has already been discussed in detail in XI, 1 and XII, 1. Representing the detector reading by  $I$  and the spectral sensitivity by  $s(\lambda)$ , we simply have:

$$s(\lambda) = I/E(\lambda) \quad (73)$$

Calculating the absolute value of the spectral concentration of irradiance  $E(\lambda)$  is hardly possible with monochromators and often inconvenient with filters. Relative values  $E(\lambda)_r$  are much easier to obtain. When these are known, only the relative spectral sensitivity  $s(\lambda)_r$  will emerge. Generally speaking, this method is only used for the latter purpose.

It is therefore usual to determine the spectral sensitivity of a detector by comparison with a detector of known spectral sensitivity, using a thermal detector for greatest simplicity. This measurement is often carried out in two stages.

First, using a monochromator (allowing the adjustment of any desired wavelength) the relative spectral sensitivity is determined by comparison with a non-selective thermal detector. The necessity to limit ourselves to relative values is shown by the fact that, because of the different dimensions of detectors and the spatially restricted radiation fields, it is nearly always necessary to place the detectors at different positions in the field of radiation. This makes it difficult to determine the conversion factor  $q$  (see equation (72a)).

The next step is to establish a monochromatic radiation field by means of a filter and to determine an absolute value for the spectral sensitivity by means of a non-selective thermopile of known sensitivity for the wavelength isolated. For checking purposes it is recommended that these absolute measurements are carried out not only for one, but for two or three different wavelengths.

One could ask why the measurement is not done using the monochromator with the thermopile, which would give the direct absolute values. This is, of course, possible in theory, but practical considerations weigh against it.

A vacuum thermo-element can be used for the relative measurement at the monochromator. The sensitivity is considerably higher than that of a thermopile. This is of prime importance because the radiation fluxes from a monochromator are small. The zero position is also much more satisfactory with a vacuum detector, making measurement quicker and of greater accuracy.

For absolute measurements with filters, a thermopile without window is preferably used. This measurement is always more difficult because of zero fluctuations and it takes a longer time to obtain the required measurement

accuracy. It is therefore easier to carry out this measurement only for a single or a few wavelengths.

For completeness sake, we should mention that it is sometimes useful to check the sensitivity of the thermopile used for "absolute" correction before and after the measurement by means of a total radiation standard. This measurement is described under (3).

The procedure described is naturally only one of many possible. We think particularly of the case when a selective detector is used instead of a non-selective one. The whole measurement process then becomes more complicated.

### 3. *Measurement of total sensitivity*

The sensitivity to radiation of a larger spectral range,  $\lambda_1 - \lambda_2$ , has been defined in equation (38) as overall sensitivity. Generally speaking, this always depends on the relative spectral emission of the radiator (equation (38a)) and becomes only independent and equal to the spectral sensitivity (equation (38c)), when a non-selective detector is used.

#### (a) Non-selective detectors

If a detector is known to be non-selective (because of its design or as a result of a previous measurement of relative spectral sensitivity) the measurement is relatively easy.

When measurement is carried out by comparison with a detector of known spectral sensitivity, this comparison detector may be either selective or non-selective. While for the non-selective comparison detector the overall sensitivity is equal to the spectral sensitivity (equation (38c)) and is therefore known, for the selective comparison detector it can only be calculated using equation (38a) when the relative spectral emission of the radiator is also known.

For the measurement, both detectors are placed one after the other at the same position in the field of radiation. When the sensitivity of the non-selective detector to be examined is  $s_1$ , the overall sensitivity of the comparison detector for the spectral range concerned  $s(\lambda_1, \lambda_2)$ , the corresponding detector readings  $I_1$  and  $I_2$ , the irradiance  $E$  is given by:

$$E = I_1/s_1 = I_2/s(\lambda_1, \lambda_2); \quad s_1 = (I_1/I_2)s(\lambda_1, \lambda_2) \quad (74)$$

If the comparison detector is itself non-selective,  $s(\lambda_1, \lambda_2) = s_2$ , we simply have:

$$s_1 = (I_1/I_2)s_2 \quad (74a)$$

By measuring with a radiator of known spectral emission, its total radiation will also be known; the latter is the main issue in this case.

Measurement follows the same method as described for total radiation (see equation (68a)). The detector is placed at a position in the field of radiation,

where irradiance  $E$  is known and the detector reading  $I$  is taken. The sensitivity  $s$  is then:

$$s = I/E \quad (75)$$

(b) Selective detectors

When measuring by comparison with a detector of known spectral sensitivity, the comparison detector may once more be either selective or non-selective. We have discussed this under (a). When the overall sensitivities of the two detectors are  $s_1(\lambda_1, \lambda_2)$  and  $s_2(\lambda_1, \lambda_2)$ , the corresponding detector readings  $I_1$  and  $I_2$  and the irradiance  $E$ , we have:

$$E = I_1/s_1(\lambda_1, \lambda_2) = I_2/s_2(\lambda_1, \lambda_2); \quad s_1(\lambda_1, \lambda_2) = (I_1/I_2)s_2(\lambda_1, \lambda_2) \quad (76)$$

When a non-selective comparison detector is used,  $s_2(\lambda_1, \lambda_2) = s_2$ , and we can simplify as follows:

$$s(\lambda_1, \lambda_2) = (I_1/I_2)s_2 \quad (76a)$$

If a radiator of known spectral emission is used, the total radiation  $E$  will also be known. When  $I$  is the detector reading:

$$s(\lambda_1, \lambda_2) = I/E \quad (77)$$

The total sensitivity refers to the relative spectral radiation distribution with which it was determined. It can, therefore, only be used when a radiator of the same relative spectral emission has to be measured.

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